The Hong Kong Polytechnic University

Institute of Textiles and Clothing

EFFECTS OF CLOTHING ON SKIN PHYSIOLOGY

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Skin is the largest organ of human body that acts as the interface between the internal tissues of the body and the external environment to provide barrier function and protection. Clothing, called ‘the second skin’, covers most parts of the body, most of time, in majority of the places not only providing additional shield for the body but also creating a portable living microclimate for its survival. Chinese ancient wisdoms identified clothing as the first most essential item for human living and health. However, how the skin and ‘the second skin’ interact with each other to serve the protective and biological functions is indeed a mystery and a scientific understanding of the phenomenon is still in its infancy. The aim of this research is to fill the knowledge gaps and establish a theoretical framework for delineating the effects of clothing on skin physiology.

This aim has been achieved through a systematic study to establish theoretical framework based on a thorough literature review and by undertaking a series of wear trials in mildly cold and hot environmental conditions, as well as under solar exposure. A theoretical framework of effects of clothing on skin physiology was developed by considering the potential mechanisms involved in physics, biochemistry, physiology, neuropsychology and immunology. A set of hypotheses were then proposed to explain the possible physiological interactions between clothing and skin. This theoretical framework and hypotheses were further tested by

a series of wear trials conducted in mildly cold and hot environmental conditions as well as under solar exposure.

A parallel cross-over blinded wear trial was designed and conducted in mildly cold condition to study the influence of clothing material on skin physiology. It is found that stratum corneum water content (SCWC) level is significantly higher when one wears cotton garment rather than polyester garments. Clothing material seems to significantly influence subjective sensation of *coldness* and stress level. Cotton fabric, with higher moisture sorption capacity and lower thermal diffusivity, has a positive effect on SCWC. Perception of *coldness* has a negative effect on SCWC.

To identify the effects of fabric moisture and liquid water transport properties on the skin physiology in the context of daily wear, a parallel blinded wear trial was carried out in a mildly cold environment. The results suggested that hygroscopicity of fabric significantly influences SCWC and transepidermal water loss (TEWL) in mildly cold condition. Additionally, hygroscopicity of fabric tended to influence sebum, although no significant effect on skin surface acidity has been noted. Generally speaking hydrophilicity of fabric did not significantly affect skin physiology in mildly cold environment.

To explore the mechanisms of the effects of fabric properties on skin physiological status in daily wear in mildly cold condition, statistical methods such as factor analysis and Hierarchical Linear Regression (HLR) were applied to obtain the relationships between fabric properties and skin physiological parameters such as

SCWC, TEWL, sebum and skin surface acidity. A framework was developed to describe the clothing-body interactions among fabric physical properties, sensory responses, skin physiological and neuropsychological responses in mild cold environment. It was found that hygroscopic fabric significantly increases SCWC and TEWL and decreases sebum in mildly cold condition. Fabric transport capability significantly reduces skin surface acidity by promoting heat release and reducing heat accumulation. Fabric transport capability seems to increase the *overall comfort* sensation and reduces stress. Meanwhile, fabric shearing resistance reduces *overall comfort* sensation and increases stress level. Fabric compressibility and overall moisture management capacity (OMMC) appear to enhance *overall comfort* sensation. *Overall comfort* sensation is positively related to SCWC and TEWL, while stress level is positively related to sebum.

To study effects of clothing on skin physiological response in hot environment, a cross-over blinded wear trial was also conducted, the results were analyzed statistically by using Repeated Measure-ANOVA, and its mechanisms were explored by using HLR. It was found that fabric transport capability, shearing resistance and compressibility influence human thermoregulation by affecting heat release, and microclimate humidity. Fabrics with higher transport capability significantly reduce core and skin temperature by promoting heat release from the human body to the external environment. Fabric with higher shearing resistance increases skin temperature. A framework was thus developed to describe the clothing-body interactions in terms of fabric physical properties, skin physiological, neuropsychological and thermophysiological responses in a typical hot environment.

To investigate the effects of UV blocking fabric on skin physiology, another parallel wear trial was carried out under solar exposure. It was found that that fabric with UV blocking capability reduces the acute effects of solar exposure, inhibits melanin content and erythem level as well as protects circadian rhythmicity, and increases stratum corneum hydration under UV radiation.

To reiterate, in this study, the clothing-body interactions in mild cold and hot environments as well as under solar exposure have been investigated. Two comprehensive frameworks have been developed to describe the mechanisms of the ways in which physical properties of fabric influence skin physiology, thermophysiology and neuropsychology. The outcomes of this research should contribute towards developing a scientific understanding on how clothing affects skin physiological health, comfort and protection of the body under different environmental conditions.

OUTPUT OF THE PROJECT

Refereed journal

1. **Lei Yao**, Y. Li, E. Newton, H. Tokura, M.D.I. Gohel and W.J. Chung. Implications of Fabric Water Transport Properties in Stratum Corneum Hydration under Mild Cold, *Skin Research and Technology*, accepted. (Rank 22 in 39 journals in subject category DERMATOLOGY Impact factor: 1.418)

2. **Lei Yao,** H. Tokura, Y. Li, E. Newton, M.D.I. Gohel, and W.J. Chung, Mechanism of pajama material on stratum corneum water content under mild cold conditions: explored by hierarchical linear regression. *Skin Research and Technology*, 2007. 13(4): p. 412-416. (Rank 22 in 39 journals in subject category DERMATOLOGY Impact factor: 1.418)

3. **Lei Yao,** H. Tokura, Y. Li, N. Edward, and M.D.I. Gohel, Effect of Wearing Cotton or Polyester Pajamas on Stratum Corneum Water Content under Mild Cold Conditions. *Journal of the American Academy of Dermatology*, 2006. 55(5): p. 910-912. (Rank 5 in 39 journals in subject category DERMATOLOGY Impact factor: 2.553)

4. Y. Li, T. Wong, J. Chung, J.Y. Hu, Y.T. Guan, **Lei Yao**, Q.W. Song, Y.P. Guo, E. Newton. In vivo protective performance of N95 respirator and surgical facemask". *American Journal of Industrial Medicine,* Vol. 49, No. 12, pp.1056-1065 (2006). (Rank 2 in 98 journals in subject category PUBLIC, ENVIRONMENTAL & OCCUPATIONAL HEALTH , Impact factor: 1.433)

Book chapters

5. Y. Li, H. Tokura, **Lei Yao**, and E. Newton. Clothing physiology and applications, Woodhead Publishing Limited, Abington Hall, Abington, Cambridge, CB1 6AH, UK (in preparation)

6. **Lei Yao**, Y. Li, and H. Tokura. Clothing and Skin Physiology, in Clothing physiology and applications, Woodhead Publishing Limited, Abington Hall, Abington, Cambridge, CB1 6AH, UK

7. **Lei Yao**, Y. Li, and H. Tokura. Research method, in Clothing physiology and applications, Woodhead Publishing Limited, Abington Hall, Abington, Cambridge, CB1 6AH, UK

Conference paper

8. K.J Hyun, T. Wakamura, T. Oishi, N. Muramatsu, M. Yomeda, K. Komatsu, M. Kondo, **Lei Yao**, H. Tokura, Yi Li, “Comparison of Physiological Responses of Southern China and Nara Inhabitant to Solar Exposure”. Proceedings: “Textile Bioengineering and informatics Symposium.” August 2008, Hong Kong, pp756-761

9. C. Boardmen, S. Singleton, A. Jones, Y. Li, **Lei Yao**, “Effect of Fabric Hydrophobic and Hydrophilic Treatments on Human Physiological and Sensory Responses”. Proceedings: “Textile Bioengineering and informatics Symposium.” August 2008, Hong Kong, pp 1037-1043

10. S. Singleton, **Lei Yao**, J. Hu. “Prediction of Clothing Sensory Comfort from

Fabric Properties Using Hybrid Neural-Fuzzy Model". Proceedings: "Textile Bioengineering and informatics Symposium." August 2008, Hong Kong, pp 1051-1056

11. Y. Han, J. Hu, W. Yang, R. LV, **Lei Yao**, Y. Li, "Enhancement Ultraviolet Protective Properties of Cotton Fabric Applied Nano Keratin". Proceedings: "Textile Bioengineering and informatics Symposium." August 2008, Hong Kong, pp 622-625

12. **Lei Yao**, H. Tokura, K. Hyun, T. Wakamura, T. Oishi, N. Muramatsu, M. Yoneda, K. Komatsu, M. Kondo, Y. Li, "The Effects of Ultraviolet Protective Clothing on the Physiology of Hong Kong Inhabitants". International Symposium: Effects of UV Radiation on Human Health, and UV Protection, 10 Nov 2007, Nara, Japan

13. Y.P. Guo, Y. Li, H. Tokura, T. Wong, J. Chung, D. Gohel, P. Leung, **Lei Yao**, "The physiological cost of wearing N95, surgical and protective masks with exhaust valves". Proceedings: Conference on Biomedical Engineering, Hong Kong, 21-23 September, pp.59-64 (2006)

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1.1 Introduction

Skin, that has an area of about 1.8 m^2 and average volume of 3.5 dm^3 (Agache 2004), is the largest organ of the human body. The functions of the skin include several aspects such as: environmental barrier, endocrine, temperature regulation, immunological affector and effector axis, mechanical support, neurosensory reception, and metabolism (Monterior-Riviere).

Normally the skin, always and all over, is covered by clothing, and comes into contact with clothing directly. Indeed clothing, has been called the second skin, thus playing an important role in temperature regulation and heat balance (White et al. 1988; Ha et al. 1995; Ueda et al. 1996; Choi et al. 2003) in the human body. It significantly influences human comfort sensation (Sreenivasan et al. 1991; Lau et al. 2002; Wong et al. 2004). In fact skin affects human physiology significantly with regard to: (a) clothing style (Haisman et al. 1974; Jeong et al. 1988; Li et al. 1996; Ha et al. 1998), (b) thermal properties of clothing (DRAPER et al. 1955; Blockley 1968; Inagaki et al. 1971; Haisman et al. 1974; Pascoe et al. 1994; Candas et al. 1995; Havenith et al. 1999; Gavin Timothy 2003; Li et al. 2005), (c) mechanical properties of clothing (Huchingson 1972; Young et al. 1985; Sugimoto 1991; Fournier et al. 2000; Takasu et al. 2001; Mori et al. 2002; Wong et al. 2004), and (d) specific design (protective function) of clothing

(Colin et al. 1970; Holmer 1989; Reneau et al. 1999; Cadarette Bruce et al. 2003; Smolander et al. 2004; Holmer 2006).

How does clothing influence skin physiology? What's the mechanism? To answer these two questions, we need to understand the ways in which clothing influences the human physiology. Related questions worth asking are: what is skin histology? what is skin physiology? what kinds of biomolecular are present in the skin, and how does human skin archive the functions it serves? In addition, as textile scientists, we must know whether there are ways to influence the skin functions. Thus our central question pertains to how and in what ways do clothing influence the skin physiology. The investigation undertaken to understand these influence is delineated in this thesis.

1.2 Literature review

To fully understand the background information shaping the study described in this thesis, three related aspects have been reviewed in this section including effects of clothing on human physiology, the key concepts in skin physiology, and effects of clothing on skin physiology as illustrated in Fig. 1-1.

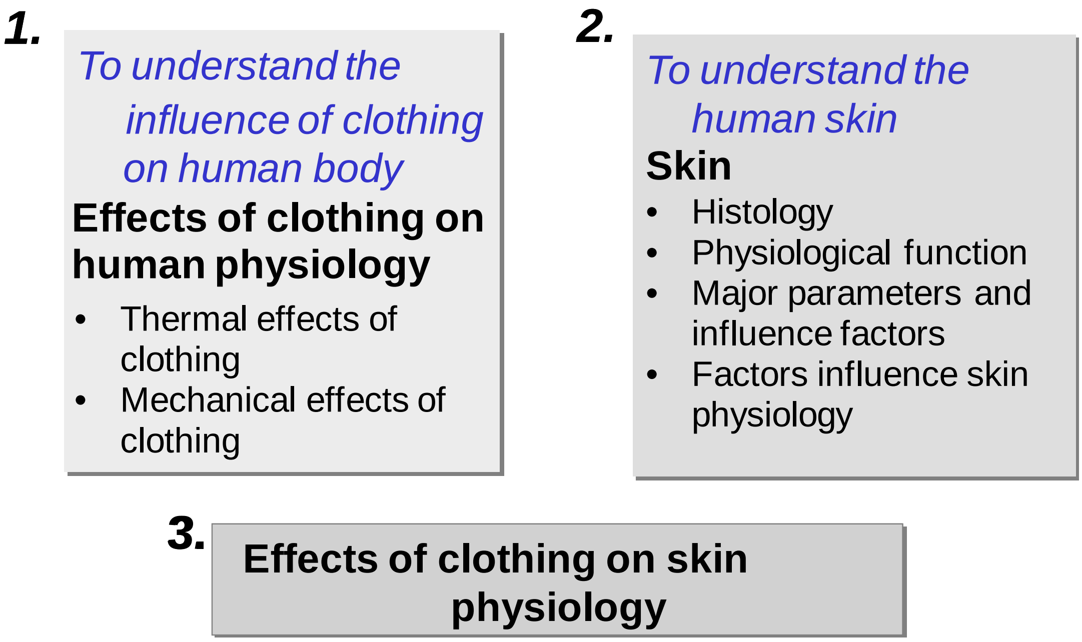


Figure 1-1 Framework of the literature review

1.2.1 Effects of clothing on human physiology

<u>*Thermal effects of clothing on human physiology*</u>

Investigation of effects of thermal properties of clothing on human physiology has been carried out from the 50s in the last century.

Theoretically, clothing may have an impact on heat loss of human body influencing Radiation (R), Convection (C), Evaporation (E) (Hensel 1959; McArdle, Katch et al. 2007). Six factors affect the insulation value of clothing, including wind speed, body movements(Parsons, Havenith et al. 1999), chimney effect, bellows effects, water vapor transfer and permeation efficiency factor (McArdle, Katch et al. 2007) (McCullough 1993; Havenith, Holmer et al. 1999; Parsons, Havenith et al. 1999; Havenith, Holmer et al. 2002; Fan, Chen et al. 2005; Ueda, Havenith et al. 2005).

Sorted by the time of publication, important references are summarized in the following table (Table 1-1):

Table 1-1 Summary of major literature on thermal effects

Paper title	Research method	Clothing	Major parameters/results	Year
Physiological data derived from a trial of a water impermeable-water vapor permeable garment. (DRAPER et al. 1955)	Wear trial	Water impermeable and water vapor permeable garment	Significant difference of post-work pulse rate, rectal temperature, skin temperature between the permeable and impermeable clothing. Mean skin temperature is the most sensitive measure.	1955
Thermoregulatory and Subjective Responses of Clothed Men in the Cold During Continuous and Intermittent Exercise. (Gavhed et al. 1991)	Wear trial	Three-layer cold-protective clothing in two thermal insulation levels	Different patterns of heat exchange of clothing sig. affected thermal responses.	1991
Effects of training and acclimation on heat tolerance in exercising men wearing protective clothing. (Aoyagi et al. 1994)	Wear trial	Protective clothing	Significant difference in overall body temperature, no sig. difference in sweat evaporation.	1994
Thermal insulation of clothing for seated and standing postures. (Nishimura et al. 1994)	Manikin	Shirts	Posture influenced total thermal insulation of clothing, surface thermal resistance at nude, the basic thermal insulation of clothing.	1994
Clothing and exercise. II. Influence of clothing during exercise/work in environmental extremes. (Pascoe et al. 1994)	Wear trial	Cold-weather clothing	In cold climate, we need to balance a clothing barrier for warmth with the potential for accumulating too much heat from exercise.	1994
Clothing, assessment and effects on thermophysiological responses of man working in humid heat. (Candas et al. 1995)	Wear trial	Clothed vs. unclothed	Sweat more with clothing, decrease in the evaporative sweat efficiency closely associated with the threshold for occurrence of core temperature.	1995
The effects of two different types of clothing on seasonal warm acclimatization. (Li et al. 1995)	Wear trial	Legs covered vs. uncovered	Significant difference in core temperature; clothing type influenced seasonal warm acclimatization to warmth.	1995

Paper title	Research method	Clothing	Major parameters	Year
Effects of two kinds of underwear on thermophysiological responses and clothing microclimateduring 30 min walking and 60 min recovery in the cold. (Ha et al. 1996)	Wear trial	Two layers underwear with two-piece long-sleeved shirt and long-legged trousers, cotton (C) vs. polyester (P)	Mean skin T sig. higher in P than in C during recovery; Absolute humidity of innermost layer and outermost layer sig. higher in P than in C during recovery; Clothing microclimate T sig. higher in C than in P during the walking and lower in C than in P during recovery; Wetness sensation is sig. higher in P than in C.	1995
Clothing microclimate temperatures during thermal comfort in boys, young and older men. (Ueda et al. 1996)	Wear trial	Adjustment of clothing on lower limbs	Lower thermoregulatory function in older men; Adjustment of clothing on lower limbs influenced maintenance of thermal comfort.	1996
Thermophysiological significance and the role of local clothing in ambient 10 degrees C environments. (Lee et al. 1998)	Wear trial	Clothing covering vs. uncovering the hands, feet, legs, thighs, buttocks and hypogastric region	Sig. difference in core temperature maintaining. Little covered clothing excluding buttocks and hypogastric regions exposure group maintained core temperature better.	1998
Thermoregulatory responses to cold: effects of handwear with multi-layered clothing. (Gonzalez et al. 1998)	Wear trial	Handwear in a cold-weather clothing system (ECWCS)	ECWCS with specific handwear furnish adequate endurance time in cold-dry ambient	1998
Thermal responses from repeated exposures to severe cold with intermittent warmer temperatures. (Ozaki et al. 1998)	Wear trial	Cold-protective jackets	Rectal temperature and toe skin temperature were sig. greater in the cool environment but, not sig. in the warm environments.	1998
Physiological significance of hydrophilic and hydrophobic textile materials during intermittent exercise in humans under the influence of warm ambient temperature with and without wind. (Kwon et al. 1998)	Wear trial	(A) Wool and cotton blend with high moisture regain, (B) 100% cotton with intermediate moisture regain, (C) 100% polyester clothing with low moistureregain. (B)	Moisture regain of fabric sig. influenced physiological heat strain during exercise and rest especially when influenced by wind.	1998

Paper title	Research method	Clothing	Major parameters	Year
Thermal characteristics of clothing ensembles for use in heat stress analysis. (Barker et al. 1999)	Secondly data	cotton and cotton/polyester blends protective clothing	Heat Stress Index: sweat rate, Metabolic rate, average skin temperature, and the environmental conditions (air temperature and vapor pressure), evaporative resistance; the clothing factor for dry heat exchange and the clothing factor for evaporative cooling were determined	1999
Clothing evaporative heat resistance--proposal for improved representation in standards and models. (Havenith et al. 1999)	Mathematic modeling	Permeable clothing, semipermeable overgarment, impermeable overgarment, tightly woven jacket	dynamic heat- and vapor resistance that can subsequently be used in standards and models for the calculation of climatic stress.	1999
The effects of fabric air permeability and moisture absorption on clothing microclimate and subjective sensation in sedentary women at cyclic changes of ambient temperatures from 27 degrees C to 33 degrees C. (Ha et al. 1999)	Wear trial	A) polyester clothing (low moisture absorption and low air permeability) B) polyester clothing (low moisture absorption and high air permeability); C) cotton clothing (high moisture absorption and high air permeability)	1) Sig. difference in clothing surface temperature 2) positive relationship between the microclimate humidity and forearm sweat rate, and the microclimate humidity at the chest for the same sweat rate was lower in C clothing than in A and B clothing.	1999
Thermal insulation and evaporative resistance of football uniforms. (McCullough et al. 2003)	Manikin	Football uniforms	Football uniforms contribute significantly to the heat load on a player.	2003
Clothing and Thermoregulation during exercise. (Gavin 2003)	Review		Topics covered thermal balance, clothing, exercise in warm to hot environments, exercise in cool to cold environment.	2003
The physiological response on wear comfort of polyethylene terephthalate irradiated by ultra-violet. (Choi et al. 2006)	Wear trial	Polyester clothing with different time period UV treatment	Suitable UV irradiation would improve comfort sensation.	2006
Effects of moisture absorption of clothing on pitching speed of amateur baseball players in hot environmental conditions. (Park et al. 2006)	Wear trial	Cotton vs. polyester/polypropylene clothing for baseball	Cotton clothing with a higher moisture regain compared to polyester and polypropylene clothing may have diminished accumulated thermal induced fatigue in the subjects.	2006

Paper title	Research method	Clothing	Major parameters	Year
Physiological comfort of biofunctional textiles (Bartels Volkmar 2006)	Review	Biofunctional textile vs. non biofunctional textile	Skin sensorial comfort is negatively affected by hydrophobic, smooth (flat) surfaces that easily cling to sweat-wetted skin, or which tend to make textiles stiffer. Recommended the use of hydrophilic treatments in a suitable concentration and spun yarns instead of filaments.	2006
People's clothing behaviour according to external weather and indoor environment (De Carli et al. 2007)	Wear trial	Clothing resistance of 0.4 clo (for ethical aspects) and an 1.6 for group A; no restrictions on clothing resistances for group B	Latitude has a good correlation between clothing insulation and external temperature in the ranges 20°–40° and −20° to −40° for NV buildings. Indoor air temperature does not influence the clothing choice early in the morning but it does influence the change of clothing during the day.	2007
Thermoregulatory responses of junior lifesavers wearing protective clothing (Sinclair et al.)	Cross-over Wear trial	Full-length Lycra stinger suit (S) vs. normal swimwear (SW)	Core temperature was greater following beach activities for S (37.78 °C ± 0.06) compared to SW (37.60 °C ± 0.07; $p < 0.05$) Heat storage while stinger suits were worn during beach activities in the absence of any differences in exercise intensity or sweat rate.	2007
Exercise physiology energy, nutrition & human performance (McArdle et al. 2007)	Text book		Clothing may have an impact on heat loss of human body influencing Radiation (R), Convection (C), Evaporation (E). Six factors affect the insulation value of clothing, including wind speed, body movements, chimney effect, bellows effects, water vapor transfer and permeation efficiency factor.	2007
Thermal insulation and clothing area factors of typical Arabian Gulf clothing ensembles for males and females: Measurements using thermal manikins (Al-ajmi et al. 2008)	Manikin	Arabian Gulf clothing ensembles	Clothing insulation of ensembles typical of the Arabian Gulf region.	2008

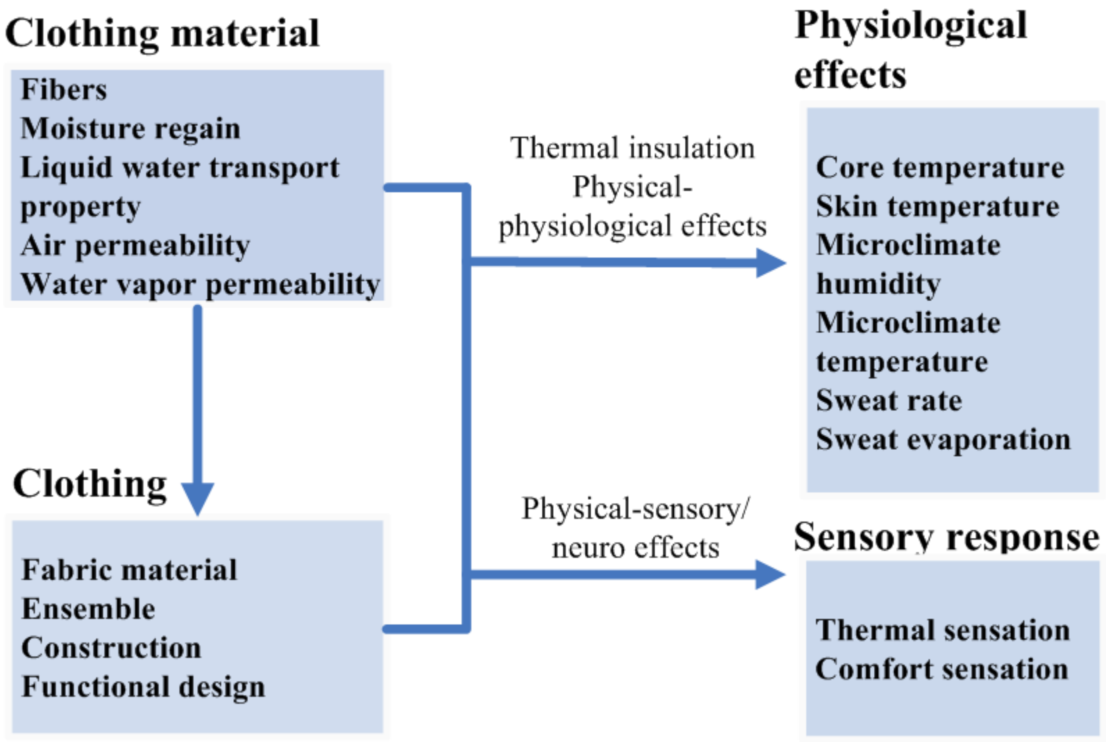


Figure 1-2 Thermal effects of clothing on human physiology

Based on the literature review in area of thermal effects of clothing on human physiology, a general image of thermal effects of clothing on human physiology was obtained (Fig. 1-2). Thermal insulation properties of fabric, such as water vapor permeability, air permeability, liquid water transport properties, are determined by fabric material, porosity, structure, thickness, and finishing. Fabric insulation properties impact not only thermal insulation properties with clothing fabric layers and style but also functional design.

Thermal insulation properties of clothing play an important role on human physiology in terms of core temperature, skin temperature, sweat rate, microclimate temperature and humidity, thermal sensation, and sensory comfort during exercise and recovery in various environmental conditions. However, questions that need in-depth investigation are: will thermal effects of clothing influence skin physiology? what would/could mechanism be? These questions perhaps have not been well interpreted.

Mechanical effects of clothing on human physiology

From late of the 1990s, effects of mechanical properties of clothing on human physiology have been studied with reference to different compression clothing such as girdle, compression brassiere, stocking, and tight-fit clothing (i.e. sportswear, jacket). The major research results are summarized in Table 2-2.

Summary

Fabric elasticity, friction, bending, shearing and compression properties and clothing style as well as functional design govern mechanical properties of clothing (i.e. compression), which influence the pressure and pressure distribution on human body, induce physical-physiological effects on human physiology in terms of peripheral blood flow, endocrine response, digestive function, core temperature, skin temperature, and wound recovery. Meanwhile, mechanical properties of fabric induce physical-sensory/nervous effects on sensory response influencing sensations of *tactile*, *prick*, *smooth*, *softness*, and *overall comfort* as well as autonomic nervous system activity of human beings during wearing.

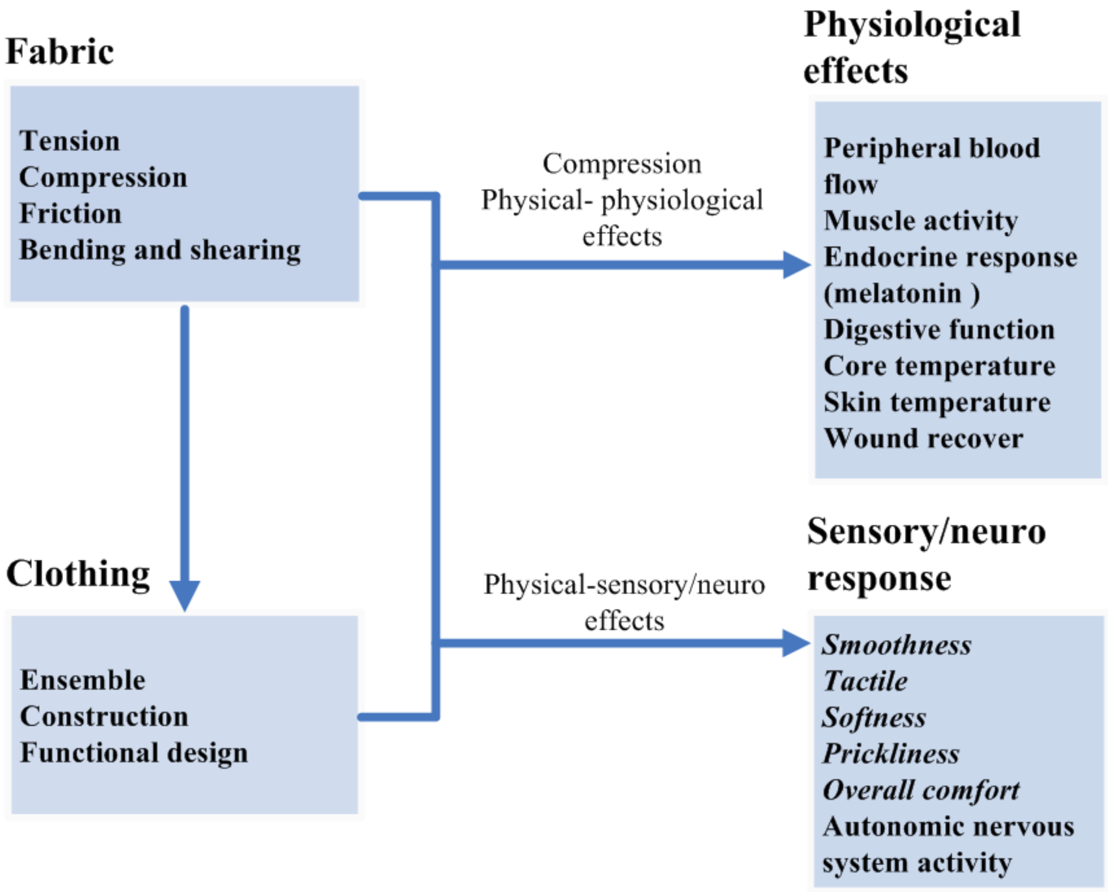


Figure 1-3 Mechanical effects of clothing on human physiology

Beside mechanical effects of clothing on skin sensory response and wound recovery, what are the mechanical effects on other skin physiological aspects, such as barrier function, the most important function of skin? Systematic study needs to be carried out to answer this question.

Table 1-2 Summary of major literature on mechanical properties

Paper title	Research method	Clothing	Major parameters	Year
Effectiveness of intermittent pulsatile elastic stockings for the prevention of calf and thigh vein thrombosis in patienis undergoing elective knee surgery (Hull et al. 1979)	Clinic trial	Compression stocking	Significantly reduced deep postoperative venous thrombosis development patients who underwent elective knee surgery patients.	1979
Comparison of leg compression stocking and oral horse-chestnut seed extract therapy in patients with chronic venous insufficiency (Diehm et al. 1996)	Clinic trial	Compression stockings class II	Significant oedema reductions in compression stocking group.	1996
Inelastic versus elastic leg compression in chronic venous insufficiency: A comparison of limb size and venous hemodynamics (Spence et al. 1996)	Clinic trial	Elastic stockings and an inelastic compression garment	Elastic compression has a significant effect on deep venous hemodynamics by decreasing venous reflux and improving calf muscle pump function when compared with compression stockings, which may exert their primary effect on the superficial venous system.	1996
Direct measurement of cutaneous pressures generated by pressure garments (Giele et al. 1997)	Clinic trial	Pressure garment	Pressure garments generate an increase in subdermal pressures in the range 9-90 mmHg depending on the anatomical site. Garments over soft sites generate pressures ranging from 9 to 33 mmHg. Over bony prominences the pressures range from 47 to 90 mmHg.	1997
'Putting the pressure on': a study of compression sleeves used in breast cancer-related lymphoedema (Williams et al. 1999)	Review	Compression garments	Discuss problems in previous studies such as sample size, wide variation, and so on.	1999
Effects of skin pressure applied by cuffs on resting salivary secretion. (Okura, Midorikawa-Tsurutani et al. 2000)	Wear trial	Loose-fitting experimental garments applied air-inflated cuffs and rubber tape	Digestive time longer with pressure; Pressure influence the digestive response by decreasing the amount of saliva via the autonomic nervous system.	2000

Paper title	Research method	Clothing	Major parameters	Year
The effects of skin pressure by clothing on whole gut transit time and amount of feces. (Takasu et al. 2000)	Wear trial	Girdle	Pressure from clothing prolonged whole gut transit time and reduced amount of feces.	2000
Effects of skin pressure by clothing on digestion and orocecal transit time of food. (Sone et al. 2000)	Wear trial	Tight-fitting girdle	Clothing skin pressure has an inhibitory effect on the absorption of dietary carbohydrate in the small intestine, but no effect on the orocecal transit time of a meal.	2000
Field studies on inhibitory influence of skin pressure exerted by a body compensatory brassiere on the amount of feces. (Lee et al. 2000)	Wear trial	Compensatory brassiere	Amount of feces was significantly smaller in group with pressure.	2000
The effects of skin pressure by clothing on circadian rhythms of core temperature and salivary melatonin. (Lee et al. 2000)	Wear trial	Foundation garments (girdle and brassiere)	1. Rectal temperatures were significantly higher when wearing foundation garments. 2. Salivary melatonin level was lower in foundation garments group. 3. Mean urinary noradrenaline excretion was significantly lower wearing foundation garments ($p < .05$), but mean urinary adrenaline excretion was not different.	2000
Skin tensile strength modulation by compressive garments in burn patients. A pilot study. (Fournier et al. 2000)	Clinic trial	A computerized suction device delivering three 5 s cycles of 500 mbar depression	Garment compression therapy alters the tensile strength in the skin of all test sites	2000
Effect of skin pressure by clothing on small bowel transit time. (Takasu et al. 2001)	Wear trial	Loose-fitting experimental garment and an additional tight-fitting girdle	Skin pressure from clothing has no effect on the passage rate of food through the small intestine	2001
Effects of clothing pressure caused by different types of brassieres on autonomic nervous system activity evaluated by heart rate variability power spectral analysis. (Miyatsuji et al. 2002)	Wear trial	A conventional higher skin-pressured brassiere vs. a newly devised low skin-pressured brassiere	Higher clothing pressures group have a significant lower autonomic nervous system activity.	2002

Paper title	Research method	Clothing	Major parameters	Time
Compression of body by clothing--increase in urinary norepinephrine excretion caused by foundation garments. (Mori et al. 2002)	Wear trial	100% cotton jacket (tight clothes, TC) or a 100% cotton T-shirt (loose clothes, LC).	(1) Urinary excretion of adrenaline, noradrenaline and cortisol in TC group was significantly higher. Heart rate in TC group was significantly higher; (2) nocturnal urinary melatonin excretion was significantly greater in the TC group.	2002
A systematic review of pneumatic compression for treatment of chronic venous insufficiency and venous ulcers. (Berliner et al. 2003)	Review		The available data cannot be relied on to inform the optimal choice of compression therapy or optimal protocol for patients with chronic venous insufficiency or venous ulcers.	2003
Evaluation of a lower-body compression garment. (Doan Brandon et al. 2003)	Wear trial	Loose-fitting vs. custom-fit compressive shorts	Skin temperature increased more and at a faster rate during a warm-up protocol, and muscle oscillation was decreased during vertical jump landing; Countermovement vertical jump height increased during wearing custom-fit compressive garment. The elasticity of the compressive garment provides increased flexion and extension torque at the end range of extension and flexion, respectively, and may assist the hamstrings in controlling the leg at the end of the swing phase in sprinting.	2003
Multi-layer Compression: Comparison of Four Different Four-layer Bandage Systems Applied to the Leg. (Dale et al. 2004)	Wear trial	Four different four-layer bandage systems	The final pressure achieved by a multi-layer bandaging system is the sum of the pressures exerted by each individual layer. Each of the systems exerted different final pressures and gradients and different changes with posture change.	2004
Influence of fabric mechanical property on clothing dynamic pressure distribution and pressure comfort on tight-fit sportswear. (Wong et al. 2004)	Wear trial and mathematic molding	Tight-fit sportswear	Pressure increases significantly around the waist girth until it passes through body pelvis during the wearing process. Pressure begins to increase for other tested body locations. Pressure distribution was not uniformly distributed and high-pressure zone was concentrated. around the waist girth at the end of the wearing process	2004
The effect of clothing on inhalation volume. (MacHose et al. 2005)	Wear trial	Tight, restraining clothing	Tight clothing significantly interferes with diaphragmatic breathing	2005

Paper title	Research method	Clothing	Major parameters	Time
Fabric Touch Tester: Integrated evaluation of thermal-mechanical sensory properties of polymeric materials. (Hu et al. 2006)	*In-vivo* testing	Fabrics	Fabric compression properties account for 69.5%, 77.0% and 66.7% of the variance in smoothness, softness and prickliness perceptions respectively.	2006
Knee versus Thigh Length Graduated Compression Stockings for Prevention of Deep Venous Thrombosis: A Systematic Review. (Sajid et al. 2006)	Review	Compression stocking	Knee-length graduated stockings can be as effective as thigh length stockings for the prevention of deep venous thrombosis, whilst offering advantages in terms of patient compliance and cost.	2006

1.2.2 Skin physiology

<u>Histology</u>

Skin is composed of three primary layers, the outer layer epidermis, which provides waterproofing and serves as a barrier to infection; the middle layer dermis, which serves as a location for the appendages of skin; and the inner layer hypodermis. (Fig. 1-4)

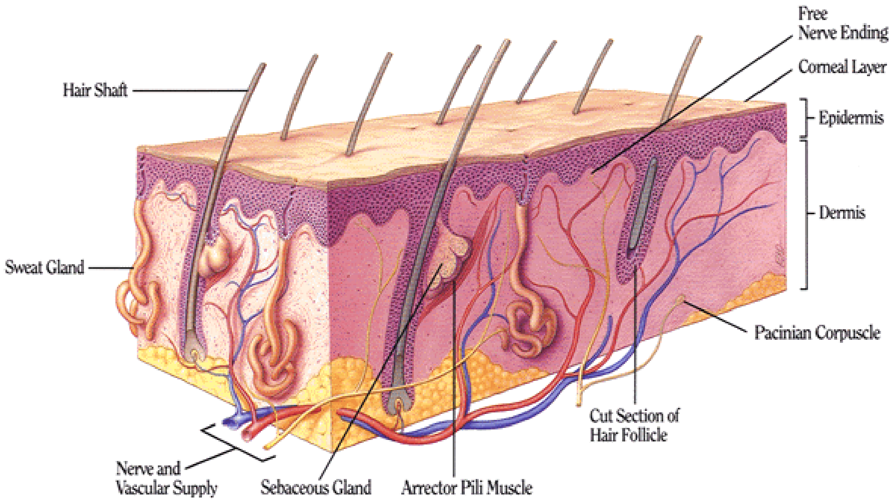


Figure 1-4 Histology of skin

(Adapted from www.homestead.com/ doctorderm/skinanatomy.html)

- Epidermis

Epidermis consists of five layers from bottom to top: the basal cell layer, the spinosum cell layer, the stratum granulosum, the stratum lucidum, and the stratum corneum. These layers work together contribut to incessant reformation of the stratum corneum. The process of single layer columnar cells in the stratum basal of epidermis constantly divides pushes older cells on a migration toward the surface of skin, and thus the stratum corneum formation (Menon 2002). The process is thought to require a period of 26-42 days (transission time) (Ryan 1991).

Stratum corneum (stratum disjunctum) is the outer most layer of human skin, which typically has about 18 to 21 cell layers (Menon 2002). It is the actual interface between the outer surface of our body and the environment. The cell and its secreted contents give it a brick-and-mortar organization (Williams et al. 1993). Figure 1-4 illustrates the major components in the stratum corneum. The corneocytes are devoid of lipids or organelles, but are filled with structural proteins (keratin filaments) and active small molecules (Elias et al.). (Fig. 1-5)

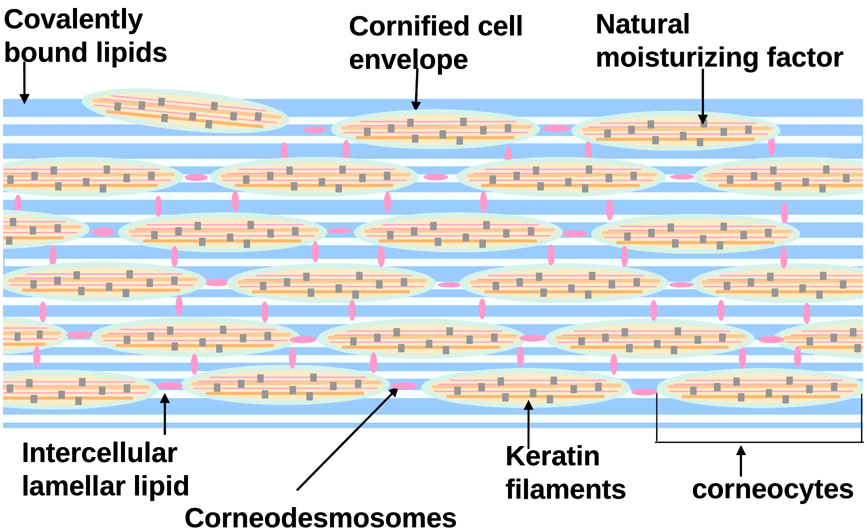


Figure 1-5 Brick-and-mortar organization of stratum corneum

(Modified based on http://dermatology.about.com/od/anatomy/ss/sc_anatomy_3.htm)

The cornified cell envelope structure provides a vital physical barrier to tissues in mammals and consists of a 10 nm thick layer of highly crosslinked insoluble proteins. The cell envelope and extracellular lipids (ceramide) are essential for effective physical and water barrier function in the skin (Kalinin et al. 2001).

Corneodesmosomes are intercellular attachment plaques, joining cornified keratinocytes together, and are responsible for cohesion of the stratum corneum. The breakdown of these intracellular connections allows for normal desquamation (Haftek 2003). The breakdown is a process of proteolysis of the corneodesmosomal proteins (Lundstrom et al. 1994; Steriotis et al. 2002). A number of enzymes are present in the intercellular regions of the stratum corneum, such as Stratum Corneum Chymotryptic Enzyme (SCCE), Stratum Corneum Tryptic Enzyme (SCTE), Stratum Corenum Thiol Protease (SCTP) and aspartic protease Cathepsin D (Charalambopoulou et al. 2002; Caubet et al. 2004). The enzymatic activities are influenced by factors such as pH (pH gradient) (Hachem 2003), water content and state, temperature, ionic strength (Ca^{2+}), coenzymes (ATP, NAD, FAD…) etc. (Steriotis et al. 2002). This suggests that skin surface acidity, water content and temperature could influence the renewal of stratum corneum.

In stratum corneum, organic acids (such as lactic acid), urea, salts, and amino acids derived from degradation of the protein filaggrin in the lower regions of the stratum corneum are as cold as natural moisturizing factors which could bind water molecule, and contribute significantly towards maintaining the water content of stratum corneum (Leyden et al. 2002).

- Dermis

The dermis is the connective tissue that provides skin pliability, elasticity and tensile strength. The major components of the dermis are collagen fibers, elastic fibers, and an interfibrillar gel of glycosaminproteoglycans, salts and water (Odland 1991). All components work together as a network. This mesh-like network is composed of structural proteins (collagen and elastin), blood and lymph vessels, and specialized cells called mast cells and fibroblasts. These are surrounded by a gel-like substance called the ground substance, composed mostly of glycosaminoglycans, which plays a critical role in the hydration and maintenance of moisture levels within the skin. Other cells in dermis are mast cells, and macrophages, which are related to immunological activity of skin.

Meanwhile, blood vessels, lymph vessels, and nerves are intertwined throughout the dermis along with glandular structures such as sebaceous glands, sweat glands, and hair follicles. The blood vessels, by constricting or dilating, control the thermoregulation of the body thus conserving or releasing heat.

Skin function

The physiological functions of the skin include: barrier function, cutaneous sensation, thermoregulation function, metabolism function, and immunological function (Peter 2003).

Barrier function

The most important function of the skin is forming a barrier between the interior of the body and the environment. It sustains the integrity of the body by protecting it from outside physical, chemical and microbiological damage and from the loss of essential body substances, such as water (Peter 2003).

The barrier function could be influenced by temperature, skin hydration, skin site, age, and skin diseases (Peter 2003). Among these, stratum corneum hydration and lipids play important role in barrier function. In fact water and lipids are necessary for stratum corneum plasticity/repairing and for limiting water transport across skin respectively.

- Cutaneous sensation

As many as 1000 sensory nerve fibers are innervated around 1 cm^2 of skin (Lynn 1991). The nerve ending of different sensory neurons mediates sensations such as touch, pressure, heat/cold, and pain. Based on the type of stimulus energy, the receptors could be divided into mechanorceptors and thermoreceptors. Most of these are unmyelinated nerve fibers that are responsible for crude somatosensory mechanical sensation. Although far fewer in number, the large myelinated (group II) sensory fibers encode the important sensory qualities of touch, vibration, and pressure. The sensations of temperature and pain are encoded by small myelinated (Aδ) fibers and unmyelinated (C) fibers.

Mechanoreceptors

The mechanoreceptors generate nerve impulses when deformed by a mechanical force such as touch, pressure (including blood pressure), vibration, stretch, and itch. Sensations of touch are mediated by naked dendritic endings, called Ruffini endings and Merkels' discs. Sensations of touch and pressure are also mediated by dendrites that are encapsulated within various structures, including Meissner's corpuscles and pacinian corpuscles (Fox 2006) (Wang 2001).

Mechanical stimulation from around hair follicles or throughout skin is provided by the free nerve endings. They are unspecialized, unencapsulated, afferent nerve ending, and they have no complex sensory structures. These are responsible for the detection of temperature, mechanical stimuli (such as pressure), pain (nociception), and information about touch. Some free nerve endings can also detect stretch stimuli (Fox 2006) (Wang 2001).

<u>Thermoreceptors</u>

Thermoreceptors detect changes in temperature. Specific nerve endings, myelinate (Aδ) and unmyelinated (C) fibers, feel heat and are present within specialized cells and free nerve endings in the human skin and tongues of human (Guyton et al. 2006){Henschel, 1949 #1182; Hensel, 1974 #1180}{Zotterman, 1953 #1}. Separate receptors encode warm and cold sensation discretely and receptively.

Warm fibers are active when the skin temperature is between 30°C and 49°C. The steady-state firing rate of warm fibers reaches a peak at temperatures of approximately 43-44°C. Cold fibers are active when the skin temperature is between 10°C and 40°C. The steady-state firing rate of cold fibers reaches a peak at the temperature of about 24°C. Extreme temperatures stimulate cold fibers as well as pain fibers, producing a mixed sensation of cold and pain. Warm and cold fibers transiently change their firing rate when skin temperatures change (Guyton et al. 2006).

The cold and warmth receptors are located immediately under the skin. In most areas of the body, cold receptors are more in number than warmth receptors (Guyton et al. 2006).

Sensation & perception

Incoming signals from sensory receptors are sent to our brain after they are processed by our senses, gathering information from mechanical, thermal, light and other receptors. Stimulation of sensory nerve fiber produces sensation only when the stimulation energy exceeds the threshold. The threshold is the point where the stimulus becomes noticeable to receptor, and allows the brain to perceive the stimulus accurately. The presentation of multiple tactile stimuli can produce cross-stimulus interactions, which can occur over both space and time (Weisenberger 2001). The thermal sensation is detecting a change in skin temperature from some initial points as the skin is already at some temperatures even before a thermal stimulus is applied. The detection of a thermal stimulus will depend on the rate at which the stimulus changes the ambient skin temperature. Thermal sensitivity shows attributes of spatial and temporal summation so that increasing the area or the duration of the stimulus results in lower thresholds (Stevens et al. 1977).

Perception refers to the process of acquiring, interpreting, selecting, and organizing sensory information. We sense the objective world, but our sensations map into provisional percepts.

The receptors pass information via primary afferent fibers from the periphery to more central structures via the spinal cord (Weisenberger 2001).

Role of skin in thermoregulation

From the thermal balance equation of human body (Gavin Timothy 2003), we get:

$$\pm S = M - (\pm W) - E \pm K \pm C \pm R\left(\frac{W}{m^2}\right)$$

Where: S is heat storage, M is metabolism, W is positive or negative work, E is evaporation, K is conduction, C is convection and R is radiation.

At 22°C ,50% humidity at metabolic rate of 70W/m^2, during heat flow by conduction is not taken into account, evaporation (respiratory and skin evaporation) shear 30% of heat release, and radiation and convection contribute 30% and 40% heat release respectively (ISO7933, ISO7730). It also be reported that 40% of heat loss is due to evaporation, conduction and convection, whilst under rest conditions at 21°C 60% humidity is due to radiation (Tortora et al. 1996).

- Immunological function

As skin contains immune cells and structural defenses, it can be classified as a fully functioning immunologic unit, which is called 'Skin Immune System (SIS)'. It was introduced to cover all components involved in cutaneous immune reactions (Bos 2005).

Major skin physiological parameters

- Stratum corneum water content (SCWC)

The skin is mainly composed of protein and lipids, including keratin, collagen, ceramides, cholesterol, free fat acids and some small molecular weight water-soluble components. The small molecular weight water-soluble components, such as moisturizing factors (amino acids, urea, lactic acid and salts) can bind water, to keep stratum corneum moisturised. Water content in stratum corneum is relatively lower compared with viable epidermis (Warner et al. 1988). The molecular basis for the reduction of water content is presumably related to the differentiated keratinocytes, hydrolyses and degraded nucleic acids, proteins and phospholipids that might reduce the number of chemical groups which can bind water(Schaefer et al. 1996).

In human skin stratum corneum, water is hydrogen bonded either to biomolecules (keratin) or the bonding is intermolecular to other water molecules (Marechal 1997; Gniadecka et al. 1998). The intermolecular water also is called free water. It occupies about 20% of stratum corneum water (Gniadecka et al. 1998; Leveque 2005). Free water molecules are hydrogen bonded to other water molecules with a tetrahedral structure in stratum corneum. Bound water holds about 80% of water in human stratum corneum (Gniadecka et al. 1998; Leveque 2005), and accounts for 34% of normal stratum corneum dry weight (Bulgin et al. 1967; Kalkley 1972). The hydrogen in water molecules bond to polar head groups of the lamellae; however, there is no free water between the lamellae. Most of the water in the stratum corneum is inside the corneocytes (Wertz 2004).

Water content in stratum corneum is influenced by a number of endogenous factors. Firstly, the stratum corneum gains water from underlying viable layers of epidermis and dermis to maintain its proper hydration status (Ma et al. 2002). Secondly, water-holding properties of corneocytes are influenced by the rate of proteolysis (fillagrin breakdown), leading to the formation of a blend of amino acid termed as natural moisturizing factors(Rawlings et al. 1994). Thirdly, lipids in stratum corneum ceramides, cholesterol and fatty acids play an important role in maintaining skin barrier (Menon et al. 1997). Other factors, such as age (K. P. Wilhelm et al. 1991; Harvell et al. 1994) and humidity of the environment (Potts 1986; Takenouchi et al. 1986) also influence the water content in stratum corneum (SCWC).

In addition to the above factors, skin renewal also could influence skin hydration. Continual renewal is an essential feature that helps maintain the integrity of this barrier tissue. Epidermal keratinocytes undergo a process of proliferation followed by differentiation to produce new cells, corneocytes, at the base of the stratum corneum. Under normal conditions, the rate of keratinocyte proliferation is precisely matched by the shedding of the old corneocytes at the skin surface thereby maintaining a constant tissue thickness. This shedding process is termed desquamation and occurs as a result of the degradation of the cohesive links binding the corneocytes (Charalambopoulou et al. 2002). When the shedding process is slower than the kerationcyte proliferation rate, the stratum corneum will be getting thicker, and dry skin could occur, such as chapped skin in winter.

The water content in stratum conreum is affected by exogenous factors, such as environmental humidity (Potts 1986). In different environmental humidity, it has been demonstrated that the water contents in stratum corneum are different because of swelling mechanisms for both lipid and protein regions in stratum corneum (Charalambopoulou et al. 2002). Osmotic forces play a role in the uptake of water by human skin as claimed by Patricia et al. (Patricia et al. 2004).

According to the water content of stratum corneum, water would have two different types of effects. One is its structuring effect on the lamellar bilayers when the water content up to 34%, and when the water molecules are bound to proteins. Another is to result in totally swollen SC membrane, damaging both cell and intercellular space at saturation (Steriotis et al. 2002). Corneocyte swelling can be readily understood in terms of water moving intracellularly in response to osmotic gradients. Corneodesmosome degradation is known to be a function of water exposure (Rawlings et al. 1995; Warner et al. 1999). It was found that extended water exposure leads to extensive disruption of stratum corneum intercellular lipid lamellae; outer layers of the epidermis become hydrated, and corneocytes swell (Warner et al. 2003). This phenomenon of prolonged water contact causes irritant contact dermatitis (Suskind et al. 1965), leading to intense dermatitis (Hurkmans et al. 1985).

- Transepidermal water loss (TEWL)

The free or very weakly bound water in the intercellular spaces and water from the physiological dehydration of corneocytes attracted to the surface by the lower relative humidity of the atmosphere, passes from inside of body through the stratum corneum to the surrounding atmosphere via diffusion and evaporation processes. It is called Transepidermal water loss (TEWL) (Agache et al. 2004; Pirot et al. 2004). TEWL is applied as a parameter for describing stratum corneum barrier function when there is no sweat gland activity. Once sweating gland is activated, the data reflects liquid water evaporation on the skin surface instead of barrier function (Agache et al. 2004; Pirot et al. 2004).

In-intro research has studied transepidermal water loss under steady-state and non-steady-state relative humidity (McCallion et al. 1994). It has demonstrated that under steady-state conditions, the rate of TEWL is constant and could be predictd by Fick’s first law of diffusion.

$$TEWL = D_s \frac{\Delta C}{L} t$$

Where TEWL is the transepidermal water loss in (kg.m^{-2}), D_s is the diffusion coefficient of water vapor through the stratum corneum, L is the thickness of the stratum corneum, and ΔC is the vapor concentration gradient, t is time in second.

Under non-steady-state relative humidity, the following equation can be derived from the First Fick's law and the mass balance:

$$TEWL = \frac{\partial C \partial L}{\partial t}$$

Where t is time in second. C is the water vapor concentration under stratum corneum. Diffusion coefficient D_s is temperature dependent.

Studies have found that higher skin temperature could raise TEWL (McCallion et al. 1994; Thiele et al. 2003), low skin temperature, on the other hand, may result in misleadingly low TEWL levels (Halkier-Sorensen et al. 1995). An equation is presented as below to arrive at the actual value of TEWL, which could be calculated based on TEWL value at skin temperature of 30 °C (Wilhelm 1995):

$$\log TEWL_{30} = \log TEWL_T + 0.035(30 - T)$$

Where $TEWL_T$ is TEWL at a given skin temperature T; $TEWL_{30}$ is corrected TEWL for a standard reference temperature of 30 °C.

- Skin surface acidity (pH)

Skin surface pH is a measure of the H^+ concentration in the watery solution present on the surface. It is expressed by the logarithmic reciprocal of the H^+ concentration. In humans, newborn SC displays a near-neutral surface pH, which declines rapidly over the first postnatal month. In adults, surface pH starts at 4.5-5.3, increasing by about 2-3 units until it reaches 6.8 in the lower SC (Joachim W. Fluhr et al. 2002).

The acidity of the skin surface is an important part of the skin surface ecosystem, which operates as a protection against microbiological or chemical aggressions (Agache 2004). It involves: (1) SC permeability barrier homeostasis (Hachem et al. 2003), (2) extracellular lipid processing (Kitagawa et al. 1995;

Bouwstra et al. 1998; Fluhr et al. 2001; Sznitowska et al. 2001), (3) SC integrity/cohesion (Fluhr et al. 2001; Hachem et al. 2003) (Integrity is defined as a measure of resistance to dissociation of adjacent corneocytes by tape stripping and cohesion is a related index defined as the amount of protein removed per stripping), (4) proteolytic processes which is pH dependent, leading to desquamation (Fluhr et al. 2001), and (5) an acidic pH provideing important antimicrobial resistance (Joachim W. Fluhr et al. 2002).

Both exogenous and endogenous mechanisms have been hypothesized to contribute to SC acidification (Joachim W. Fluhr et al. 2002). Three endogenous mechanisms have been identified which could influence SC pH, and these are: (1) the histidine-to-urocanic-acid pathway, (2) the phospholipid-to-FFA pathway, and (3) the sodium proton antiporter (NHE1) (mauro 2006). Other endogenous factors, such as racial differences, topographical variation, gender differences, developmental and age-related changes, have also been reported. Exogenous factors, like the use of detergents and cleaning products, can also change the surface pH (Ananthapadmanabhan et al. 2003).

Histidine-to-Urocanic-acid pathway is largely responsible for SC hydration (Rawlings et al. 1994; Harding et al. 2000). In the cornification process, filaggrin undergoes proteolysis to free amino acids, urocanic acid, pyrrolidone carboxylic acid, and ornithine/citrulline/aspartic acid, which make up much of the osmotically active material that largely accounts for the ability of the stratum to remain hydrated (Scott et al. 1986). Enzymatic processes of nonoxidative histidine deamination have been identified as contributing to stratum corneum acidification (Krien et al. 2000). The enzyme histidine-ammonia-lyase is the key in the process. The main product of the histidine deamination is the trans-urocanic acid, which plays an important role in skin physiology by maintaining stratum corneum hydration and affecting ultraviolet protection (de Fine Olivarius et al. 1996; Hurks et al. 1997; Hug et al. 1998). But, the histidine-to-Urocanic acid pathway does not entirely explain the acidity of the skin. The second pathway contributing to skin acidity is phospholipid-to-Free fatty acid pathway. The products of this pathway is a pool of free fatty acids, which not only the influence the normal stratum corneum acidification, but also play an important role in the dual functions of stratum corneum integrity and cohesion (Fluhr et al. 2001). The third is the sodium proton antiporter (NHE1) (Hachem et al. 2005). NHE1 is the only one Na(+)/H(+) antiporter isoform in keratinocytes and epidermis, that regulates intracellular pH. It is an essential endogenous pathway responsible for stratum corneum (SC) acidification (Martin J Behne et al. 2002).

Indeed the acidity in skin surface also could be influenced by sweating. Sweat is a filtrate of plasma that contains electrolytes (such as potassium, sodium, and chloride) and metabolic wastes (like urea and lactic acid). During exercise, or in higher temperature, sweat production will be higher, as cells in sweat gland do not have enough time to reabsorb all of sodium and chloride from the primary secretion. The contents of sweat except sodium, chlorine and potassium, including protein and fatty acids, are closer to plasma. The pH value of this sweat is around

7.4. Different from higher sweat production, during low sweat production, such as during rest or in cool temperature, most of the sodium and chlorine from the fluid is reabsorbed by the sweat gland. Indeed sometimes there is no water reaching the skin surface. This situation is called insensible sweating. Also, the composition of this sweat is significantly different from the primary secretion. There is not as much sodium and chloride, and there is more potassium. (Freudenrich 2006)

The pH of fresh sweat ranges from 5 to 7 and becomes more acidic with evaporation. The reason could be that the acidity of the skin surface due to sweat is controlled by lactic acid and its volatile derivatives such as acetic and propionic acid. In addition, ammonia, one of the degradation products of bacterial action on sweat, evaporates quickly and the skin turns acidic due to the higher ionization constant of acetic acid. (Parra et al. 2003)

- Lipids of skin

There are three major lipid classes in stratum corneum, including ceramides, cholesterol and free fatty acids. Ceramides is synthesized during epidermal keratinocytes differentiation (Wertz et al. 1990). The source of cholesterol and free fatty acids is lipids, also called sebum, secreted from mammalian sebaceous glands, mixed with lipid from the keratinizing epithelium and forms the skin surface lipid film (SSLF), and forms a fluid film over the skin surface. The quantity of lipids from epidermal keratinocytes differentiation is relatively small, but becomes important in studies of the human skin.

The lipids are synthesized during epidermal differentiation by loss of phospholipids and the conversion of glucosylceramides to ceramides as well as AcylGlcCer to acylceramide and ω-hydroxyceramides (Hedberg et al. 1988; Madison et al. 1990). The sebum secretes and accumulates in the sebaceous gland before being excreted. It then seeps into the main skin surface, penetrates the intercellular spaces and mixes with lipids from epidermal differentiation (Agache 2004; Agache 2004), which plays a critical role in skin barrier function.

- Melanin content & erythema

Melanin is the pigment that is synehesized by melanocytes located in the basal layer of the epidermis. The amount of melanin determines our skin color, both naturally and with sun exposure (Leroy 2004). The photoprotection function of melanin is based on UV light absorption capacity (Kollias et al. 1985).

Low dose or short exposure to UV irradiation is tolerated by the skin without noticeable or clinically relevant changes. Only after reaching a certain threshold, a delayed and prolonged vasodilation develops allowing passage of lymphocytes and macrophages into the tissue and inducing an inflammatory response, which is clinically visible as erythema (Luger et al. 1990; Boelsma et al. 2001). Erythema is the most clinically apparent component of a sunburn reaction (Boelsma et al. 2001). Except race, several factors, such as skin type and hair color may be predictive of UV-induced erythema (Azizi et al. 1988).

As the maximal absorption of melanin in human takes place at 335 nm, which implies that melanin protection capacity would be more efficient against

UVA than UVB. UVA can induce an immediate pigmentation within minutes following exposure and disappears in a few hours. This immediate pigmentation reflects the individual level of constitutive pigmentation. (Leroy 2004)

Two indexes are used to describe the capacity of UV protection. One is melanin density: the density of melanin in the region down to the dermal junction and the rate in which melanogenesis occurs. The second is erythema: the level of vascularity and density of the microcirculation system (CK 2004).

- Allergen and irritant

Allergy is delayed hypersensitivity reaction, which develops IgE type antibodies. Allergy is characterized by a local or systemic inflammatory response to allergens. The allergens substance could be low-molecular weight hapten (e.g., metals, formaldehyde/formalin, epoxy). It is worth noting that formaldehyde has been applied in textiles for long time. It is a main compound in dimethylol dihydroxyethylene urea, which is used in wrinkle-free finishing cotton textiles. The remaining formaldehyde could cause allergic contact dermatitis (ACD).

Irritants refer to a physical and chemical alteration of epidermis. Such alteration is not an immunological process, which could be induced by physical contact, pressure, friction (Zhong et al. 2006; Susan et al. 2007). Chemical residual on textiles from dyeing, finishing and even washing detergent could lead to the risk of irritant contact dermatitis (ICD).

Effects of stress on skin physiology

Previous studies show that skin sympathetic nerve activity plays an important role on skin SCWC as it is sensitive to thermal stimuli, and may regulate peripheral vasoconstriction (Cogliati et al. 2000). Skin sympathetic nervous system controls thermoregulation even during sleeping (Kobayashi et al. 2003). Hydration of facial skin in human was impaired by both physical and psychological stress [14] (Altemus et al. 2001). Psychological stress has been found to inhibit the recovery of stratum corneum barrier function (Altemus et al. 2001) (Denda et al. 2000) because stress impairs both proliferation of epidermal cell (Tsuchiya et al. 1994) and sebaceous gland lipogenesis (Tsuchiya et al. 1994) following permeability barrier disruption. In mice, stress-induced impairment of barrier function is dependent on glucocorticoids released with stress (Sheu et al. 1997; Denda et al. 2000).

Effects of radiation

IR

As the natural resonant frequencies of molecules of water and organic substances are within the far-infrared (FIR) wave frequencies (wavelengths of 5 to 15 microns), and water and organic substances can easily absorb IR radiation energy (Kim et al. 2003). The ability to absorb IR and depth of penetration on the human skin corresponds with the IR wavelength, i.e. the shorter the penetration depth, the longer the IR wavelength (Bachem et al. 1931). Short wavelengths in the IR-A (1000nm) range reache the subcutaneous tissue without increasing the surface temperature of the skin markedly, whereas IR-C (3000-6000nm) is absorbed completely in the epidermal layers and causes an increase in skin temperature resulting in thermal sensations ranging from pleasant warmth to thermal burn.

Radiation in the IR-A range is associated with UVA/B radiation. the vibration and rotational energy state of molecules by IR may influence the photochemical reactions induced by UV and may thus enhance the damaging effects of UV on human skin (Schieke et al. 2003). Infrared radiation includes vasodilatations of the capillary beds and increased pigmentation in skin. The skin is normally able to dissipate a heat load imposed by IR radiation because of capillary bed dilatation, increased blood circulation, and the production of sweat (Talty 1988).

UV

UV is regarded as a harmful and naturally occurring environmental agent, which can cause sunburn, suntanning, skin aging, skin cancer and cataracts (Nishigori 2000). However, a positive effect of UV exposure is vitamin D metabolism, which plays an important role in the maintenance of human health (Fleet et al. 2004; Lehmann 2005). Immunological response of skin under UV radiation is a much discussed issue.

UV radiation reaches our skin and induces cutaneous responses including acute effects such as sunburn. Low dose or short exposure to UV irradiation is tolerated by the skin without noticeable or clinically relevant changes. A delayed and prolonged vasodilation occurs when a certain threshold is reached and lymphocytes and macrophages pass into the tissue and induce an inflammatory response; which is clinically visible as erythema (Luger et al. 1990; Boelsma et al. 2001). Erythema is the most clinically apparent component of a sunburn reaction (Boelsma et al. 2001). Epidermal thickening can occur when skin is exposed to the sun for a period of time (Bech-Thomsen et al. 1993). Solar UV exposure has been demonstrated to increase water evaporation in hairless mice (Thiele et al. 2003).

Summary

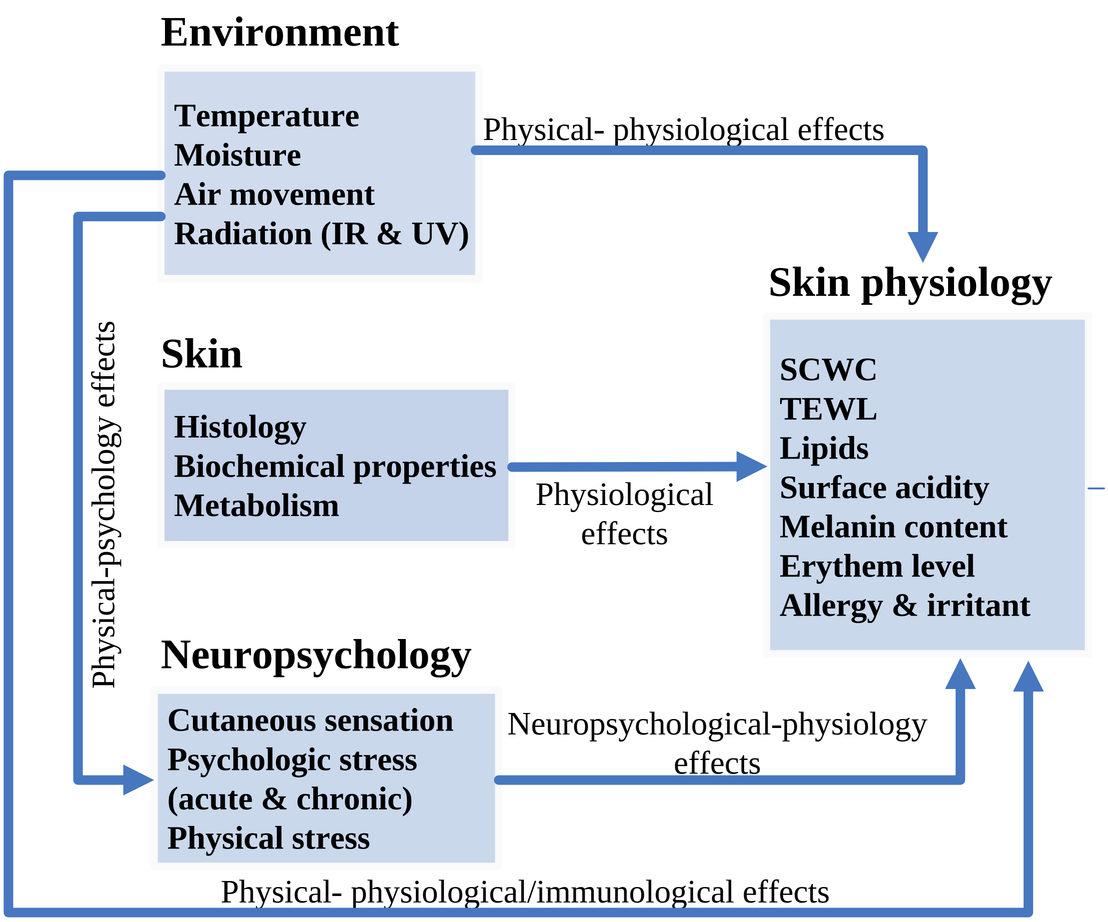


Figure 1-6 Factors influencing skin physiology

Skin plays an important role in human thermal regulation, and adjusts itself to release heat to the environment through evaporation, conduction, convection, and radiation. The histology and biochemical properties are influenced by the ways in which environmental temperature and humidity affect the skin.

Skin involves psychological activities stemming from sensory neurons receptors distributed in skin detect change in temperature and deformation of skin, stimulate sensory reaction and generate perception. Further, skin physiology would be influenced by both exogenous and endogenous factors such as temperature, water content, metabolic rate and skin surface acidity, which can impact on the activities of biochemical compounds in skin, thus influencing the skin renewal process.

Relative comprehensive studies on skin physiology have been carried out over a long period of time. Dermatologists understand the effects of clothing on skin mainly from allergen and irritant response. However, as far as clothing affects on normal skin physiology during daily wear of clothing is concerned, dermatologists need to understand more about clothing, and textiles scientist needs to know more about skin. Indeed this is a niche area that should be further explored.

1.2.3 Clothing and skin physiology

In the past century, studies of clothing effects on skin physiology have mainly focused on its dermatologic effects, such as irritation from textiles caused by physical contact, pressure, friction (Zhong et al. 2006; Susan et al. 2007), and chemical residual from dyeing, finishing and even washing detergent (Farrell-Beck et al. 1998).

There are different kinds of sources of chemicals applied in textiles dyes, finishing, treatment, and washing and each of these influences skin physiology (Bircher 2003; Fowler 2003; Hatch 2003; Matthies 2003). Detergent and surfactants products are applied on textiles for cleaning purposes. Detergents can be adsorbed onto human keratin (Matthies 2003). Dyes applied in colored fabric have been demonstrated to relate with development of contact sensitivity in thousands of cases, not only is the sensitivity due to the dye content, but also fastness of dye in fabric (Hatch 2003). Textiles have been reported to cause formaldehyde induced textile dermatitis, urticaria, and lichen amyloidosis (Fowler 2003).

Despite the prevalent problems caused by dermatology-related textile/skin interactions, minimal efforts have been devoted to investigate the influence of clothing on skin physiology in terms of health status (Farrell-Beck et al. 1998; Kiriyama et al. 2003). On the other hand, many cases show that textiles have contributed to worsening of dry or atopic skin during the winter time, but the mechanisms are not fully understood as yet (Farrell-Beck et al. 1998; Wollina et al. 2006).

It was regarded that thermalregulation, specifically, microclimate in the skin/clothing system and the skin responses relates to the moisture and heat transfer within this system, plays a critical role in skin irritation from textiles (Zhong et al. 2006), although its mechanism need to be further explored.

In the area of photoprotection, textiles are regarded as reliable means (Lautenschlager et al. 2007) (Verschooten et al. 2006). Clothing provides protection from acute and chronic sun damage (Harrison Simone et al. 2005). Fabric properties, such as fabric porosity, type, color, weight, and thickness, and garments factors such as stretch, wetness, and degradation due to laundering, do influence textiles photoprotecion performance (Hoffmann et al. 2001).

Important references have been summarized in Table 1-3.

Table 1-3 Summary of major literature on clothing skin physiology

Paper title	Research method	Clothing	Major parameters and results	Year
The effects of wearing diapers on skin. (Zimmerer et al. 1986)	Wear trial	Diaper	Wearing dry and wet cloth and disposable diaper materials has certain effects on the degree of skin wetness. With increased skin wetness, there were increased coefficients of friction and increased abrasion damage, skin permeability, and microbial growth.	1986
Identification of the physical stimulus and the neural basis of fabric-evoked prickle. (Garnsworthy et al. 1988)	Wear trial	Fabrics	The neurophysiological basis for the sensation of prickle evoked by contact of some fabrics were studied. All low-threshold mechanoreceptors were activated by fabric. The response of some nociceptors, both A delta and polymodal C, differed according to the prickliness of fabrics. Fabric-evoked prickle is the result of low-grade activity in nociceptors and that the stimuli are protruding fiber ends exerting loads of approximately 75 mgf or more against the skin.	1988
Diaper Performance: Maintenance of Healthy Skin. (Wilson et al. 1990)	Wear trial	Diaper	Different material of diapers have different performance to keep skin dry depending on their composition.	1990
Textiles and apparel in the etiology of skin diseases 1870-1914. (Farrell-Beck et al. 1998)	Review		Studies of skin disease attributed to fibers, fabrics, dyestuffs, finishes, and apparel were reviewed.	1998
The dynamics of transepidermal water loss (TEWL) from hydrated skin. (Gioia et al. 2002)	Modeling and wear trial	Diaper	The wearing of disposable diaper, when loaded with water, acts like an impermeable occlusive cover on the skin.	2002
The Frictional Properties between Fabrics and the Human Skin -- Part 1: Factors of Human Skin Characteristics Affecting the Frictional Properties between Fabrics and the Human Skin. (Kondo 2002)	*In-vivo* testing	Fabric	Skin softens when the stratum corneum water content increased. Coefficient of friction of skin is increased when stratum corneum water content is rising.	2002

Paper title	Research method	Clothing	Major parameters and results	Year
The frictional properties between fabrics and the human skin. Part 2: Influences of stratum corneum water content, hardness of skin, friction pressure, and friction speed on the frictional properties. (Kondo 2002)	*In-vivo* testing	Fabric	Fabric mean coefficient of friction is influenced by stratum corneum, it is high with increased stratum corneum water content and low with decreased stratum corneum water content.	2002
Skin physiology and textiles - consideration of basic interactions. (Wollina et al. 2006)	Review		Barrier function, immune, antimicrobial, allergy and irritant.	2006

Beside literature summarized in Table 1-3, a series systematic studies have been reported by Dr. Hatch and her group, studies undertaken since the 1980s (Hatch et al. 1987; Hatch et al. 1990; Hatch et al. 1990; Hatch et al. 1990; Hatch et al. 1990; Markee et al. 1991; Hatch et al. 1992; Markee et al. 1993; Hatch et al. 1997).

Table 1-4 Summary of study by Dr. Hatch's group

Paper I (Hatch, Wilson et al. 1987)
Focused on fabric thermal properties and thermal comfort
Result:
•Liquid water transport governed by fiber surface energy
•Thermal transfer from skin surface is strongly correlated with fabric porosity and air permeability

Paper II (Hatch, Markee et al. 1990)
Focused on fabric mechanical and thermal properties and subjective sensation
Result:
•Physical properties of fabrics are sig. different between cotton and polyester.
•Subjective sensations associated with thermal conductivity and roughness.

Paper III (Markee, Hatch et al. 1991)
Focused on effects of clothing fabric on skin (SCWC, TEWL, capillary blood flow, and skin temperature)
Result:
•Time (exercise) in experiment has sig. effects on skin parameters, and fabric has no sig. effect

Paper IV (Hatch, Markee et al. 1992)
Focused on effects of clothing fabric on subjective sensation
Result:
•Skin temperature sig. related with thermal comfort
•Wetness sensation sig. related with SCWC and TEWL
•Capillary blood flow sig. related with overall comfort

Paper V (Markee, Hatch et al. 1993)
Focused on effects of clothing fabric on TEWL
Result:
•TEWL generally increased as fabric moisture content increased
•Difference in fibers' ability to absorb moisture appear influence TEWL rate
•No sig. difference in TEWL under cotton fabric and 3.5 denier polyester

Paper VI (Hatch, Prato et al. 1997)
Focused on examining the relationship between fabric moisture content and TEWL
Result:
•TEWL is sig. different at sites covered by polyester35% moisture treatment and the cotton treatment (44% & 75%). The rate was higher at the cotton sites

Hatch and her group (Hatch et al. 1987; Hatch et al. 1990; Hatch et al. 1990; Hatch et al. 1990; Hatch et al. 1990; Markee et al. 1991; Hatch et al. 1992; Markee et al. 1993; Hatch et al. 1997) have carried out a series systematic studies (Table 1-4) since the 1980s to investigate the effects of clothing on skin physiology based on a well established research framework. Hatch and her team's study is considered to be a breakthrough in this field. They started from investigating effects of fabric thermal properties and mechanical proprieties on comfort sensation. Then, they studied the effects of fabric on skin physiology such as stratum corneum water content (SCWC), transepidermal water loss (TEWL), capillary blood flow, and skin temperature in hot humid environment during resting, exercise and recovering. However, no significant result has been found. Further, they studied effects of fabric on TEWL applied different moisture content fabric and moisture treatment material and found a significant difference on TEWL between skin covered by polyester with 35% moisture treatment and cotton with 44% and 75% moisture treatment.

Limited by understanding of biochemical physiology of skin and human physiology at the time, Hatch and her groups studied the physical effects of fabric on skin physiology by their experiments designed to look at small contacting area and short contracting time with skin. This experimental design could not include biochemical-physiology effects on skin physiology, nor did they focus on the induced effects of fabric physical properties on skin and human thermal physiological response. And, the condition of wear trial carried out in hot humid environment inhibited heat release from human body to outside, and depressed the role of thermal and moisture transport properties of fabric on skin and human physiology.

With the development of skin biochemical and physiology research after the 1990s, it was understood that the skin was mainly composed of protein and lipids, including keratin, collagen, ceramides, cholesterol, free fat acids and some small molecular weight water-soluble components. The small molecular weight water-soluble components, such as moisturizing factors (amino acids, urea, lactic acid and salts) can bind water, to keep stratum corneum moisturrised (Rawlings et al. 1994; Rawlings. 2003). Moreover, except for the above physical-physiological effects, the role of desquamation of keratinocytes in stratum corneum needs to be highlighted. A number of enzymes are present in the intercellular regions of the stratum corneum, such as Stratum Corneum Chymotryptic Enzyme (SCCE), Stratum Corneum Tryptic Enzyme (SCTE), Stratum Corenum Thiol Protease (SCTP) and aspartic protease Cathepsin D (Charalambopoulou et al. 2002; Steriotis et al. 2002; Caubet 2004). These enzymes adjust the normal desquamation of keratinocytes in stratum corneum (Haftek 2003). As the activities of these enzymes could be influenced by water content and temperature (Charalambopoulou et al. 2002; Steriotis et al. 2002), one would except that fabric not only influences microclimate humidity and temperature, but also could influence the renewal of stratum corneum by affecting the activities of the enzymes, which might further affect on skin physiology such as SCWC and TEWL.

Based on this understanding, systematic studies should be designed and carried out to investigate effects of clothing on skin physiology in daily wear to understand what kind of effects would be induced by our clothing in our daily life in terms of physical, physiological, biochemical and neuropsychological factors; and how these influence our skin physiology. Comprehensive study is also needed to help us understand effects of clothing on skin physiology from the viewpoint of physics, physiology, biochemistry, and neuropsychology.

1.2.4 Summary of literature review

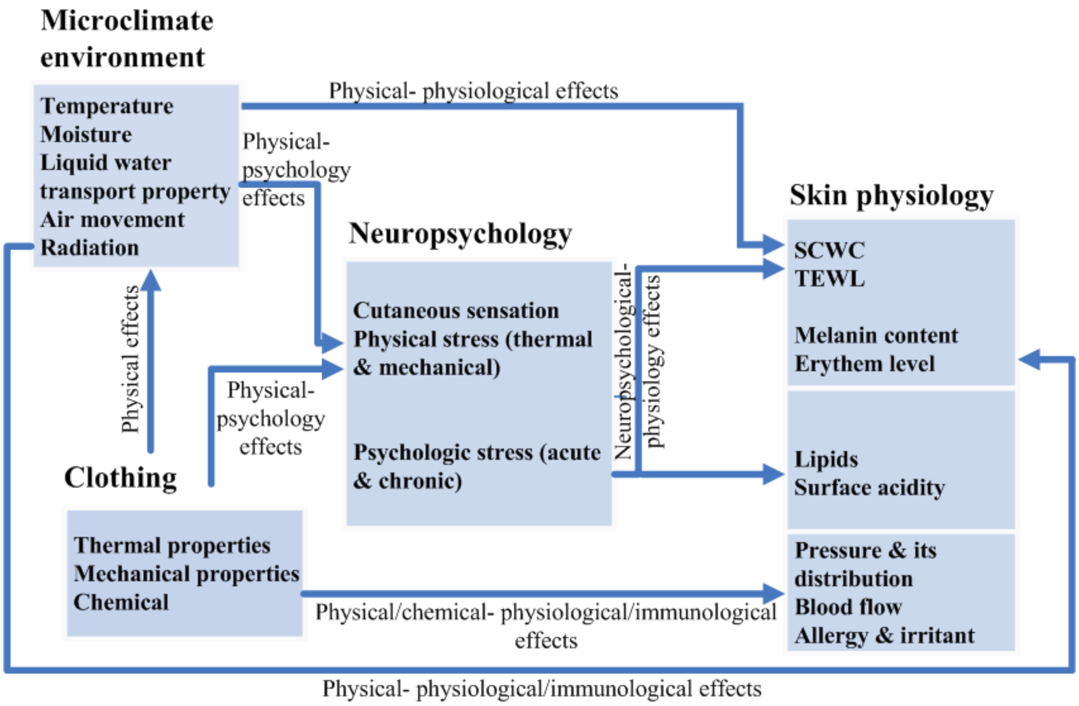


Figure 1-7 Effects of factors influencing skin physiology

Skin, as the largest organ in the human body, is affected by human physiological and psychological status, such as thermal regulation and stress. Clothing influences human physiology significantly through thermal regulation, pressure, pressure distribution, stress level, digestive system, automatic nervous system activity, and sensor perception. Skin contacts with clothing directly and for long periods of time, and in fact skin physiology parameters like SCWC, TEWL, surface acidity, skin lipids, allergen and irritant could be affected or even be induced by clothing worn in various types of climate/atmosphere either due to changing temperature/humidity or arising from contact action.

To reiterate, skin, as the biggest organ, involves most of the physiological activity of human body. We need to know the ways in which clothing influence skin physiology in areas of physics, physiology, biochemistry, and neural-psychology. Systematic investigation should be carried out to clarify the impacts and understanding the mechanism of clothing effects on skin physiology in our daily lives.

1.3 Problem statement

Through the systematic review and analysis, a general view of this research in this area has emerged. In summary, knowledge-gaps in individual areas have been identified as follows:

1. It has been understood that skin physiology is a cross-disciplinary area involving physics, biochemistry, physiology, neuropsychological and immunology. The relationship between clothing and skin physiology is not very clear. Previous studies mainly focused on physical effects (water content of fabric) on skin physiology, and its sensory effects. The influence on physiological, neuropsychological and biochemical aspects need to be further explored.

2. The roles of clothing on skin physiology in different environmental conditions have not been clearly identified.

3. The influence of clothing properties on skin physiology under different environmental conditions and its mechanisms have not been disclosed in any detail.

4. Relationships between the clothing properties, sensory response, and skin physiological parameters and other human physiological parameters have not been explored systematically.

5. The roles of UV blocking fabric on skin physiology under solar exposure have not been identified.

According to the literature review and the above summary of problematic issues, there seems to be clear implications that effects of clothing on skin physiology would be a complex framework, which needs to be explored within a cross-diplomacy framework. As a starting point, effects of fabric on skin physiology have been chosen as the focus in this study.

1.4 Originality and significance of the study

1.4.1 Originality and significance

The originality of this project is to fill the knowledge gaps identified and to establish a sound scientific understanding of the effects of fabric material/treatment on skin physiology and its health impact in our daily wear. The following significant achievements are foreseen:

- A framework of effects of clothing on skin physiology is to be developed based on literature review, and a series of hypotheses will be proposed and verified to explore the roles of clothing on skin physiology in different environmental conditions.
- A systemic research methodology will be developed to study the influence of fabric properties on skin physiology and its health impact from aspects of

physical, sensory, and physiological responses in different environmental conditions.

- Major physical properties of fabric influencing the skin physiology will be identified by wear trial in different environmental conditions; the mechanisms will be explored with the use of applied statistical methods to understand the effects of fabric material/treatment and its physical properties on human skin physiology.
- The outcome of this research may contribute significantly to the skin physiological health, comfort and safety of the wearer in our daily lives under different environmental conditions.

1.4.2 Objectives

To fill in the knowledge gaps identified above, this thesis aims to conduct a systematic study of the multiple mechanisms that interact between physical, biochemical, physiological, neuropsychological factors, in order to establish a comprehensive knowledge framework for exploring the mechanism of effects of fabric on skin physiology. The objectives with necessary detail are to:

1) Develop a framework of effects of clothing on skin physiology in terms of physical, biochemical, physiological, neural psychological, and immunological factors;

2) Clarify the effects of clothing material on skin physiology in daily wear in mild cold environment without sweating;

3) Identify relevant physical properties of fabric that may influence the skin physiology in daily wear in mild cold weather with no sweating;

4) Explore the mechanism of effects of clothing properties on skin physiological status in daily wear in mild cold weather with no sweating;

5) Study the effects of clothing on skin physiology in hot weather, and explore the mechanisms;

6) Study the effects of UV blocking fabric on skin physiology under solar exposure.

1.5 Research methodology

To achieve the objectives outlined above, the project plans to undertake the following research methodologies:

1. Developing a framework based on systematic study of physical, biochemical compounds, physiology and neuropsychology of human skin;

    Drawing on extensive literature reviews, this research sets out to build a sound scientific foundation for understanding the anatomical structures, bio-chemical, physical, physiological and sensory characters of skin, as well as factors influence the skin physiology from thermal, mechanical, neuropsychological, immunological, and physiological aspects. Additionally, a database is to be created which will provide a sound scientific basis for understanding the thermal and mechanical characters of fabric, as well as their impacts on sensory response and human physiology. A framework encompassing the effects of clothing on skin physiology is proposed which integrates both scientific understanding of skin physiology and clothing physical characters.

2. Clarifying the effects of fabric material on skin physiology in mild cold weather by conducting wear trial;

A parallel, cross-over, blinded wear trial was designed to investigate the effects of different material fabric on skin physiology in terms of skin hydration, sensory response, and on stress level in mild cold weather.

3. Identifying relevant physical properties of fabric that may influence the skin physiology in mild cold weather;

A parallel, blinded designed wear trial was designed to investigate the major properties that influence skin physiology in mildly cold condition.

4. Exploring mechanisms of fabric on skin physiology;

Statistical technique is applied to explore the mechanism of effects of fabric on skin physiology to understand the relationship among skin physiology, fabric properties, sensory response and human physiology

5. Studying role of fabric on skin physiology in hot environment where different physiological activities such as resting, running, and recovering are undertaken to understand the effects of clothing material and treatment, transport capability, and mechanical properties on skin physiology as well as human body thermal physiology;

A cross-over, blinded wear trial is design to study the effects of fabric on skin physiology and explore the mechanism by appropriate statistical technique.

6. Investigating the effects of UV blocking fabric on skin physiology under solar exposure;

A parallel wear trial is designed to investigate the effects of UV blocking fabric on skin physiology under solar exposure in terms of different response such as cutaneous, immunological and fatigue symptoms.

1.6 Thesis outline

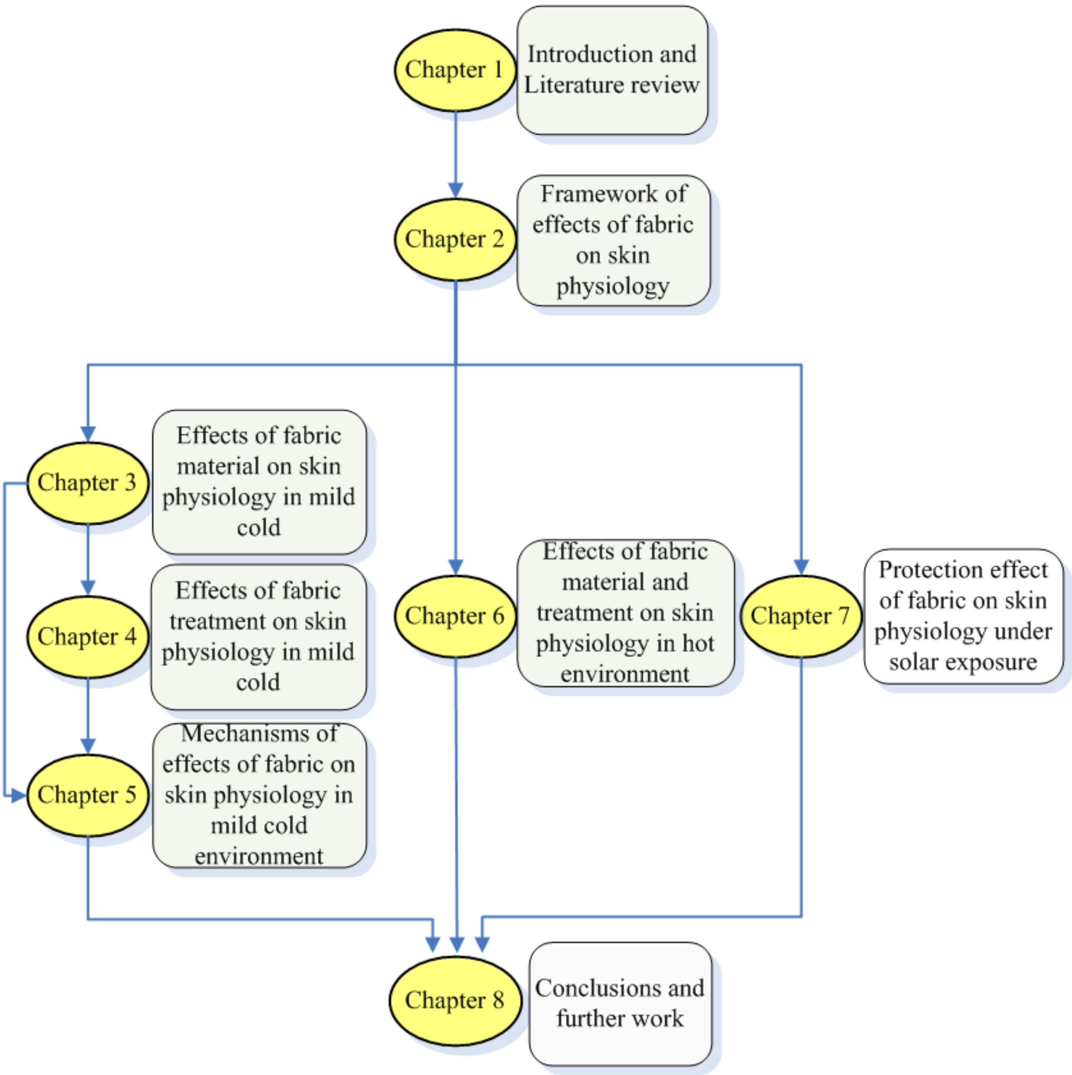


Figure 1-8 Thesis structure and framework

The thesis consists of eight chapters (Fig. 1-8). Chapter 1, above, has presented the extensive literature reviewed in relevant disciplinary areas, so as to have a scientific understanding, and through this process the chapter has identified the knowledge gaps and described the research objectives and methodologies to be adapted.

Chapter 2 proposes a framework encompassing the effects of fabric on skin physiology from a multidisciplinary perspective that includes physical, biochemical, physiological, neuropsychological, and immunological aspects, and then the chapter proposes a series of hypotheses to find out if we can predict possible causal correlation between clothing and skin physiology.

Chapter 3 extends the study of the influences of fabric material on skin physiology by conducting a parallel, cross-over, blinded wear trial to investigate the effects of fabric material on skin physiology, subjective perception, and stress level.

Chapter 4 indentifies key properties of the influence of fabric on skin physiology through the parallel, blinded wear trial to understand the influence in terms of subjective perception, and stress level.

Chapter 5 applies statistical methods, explores the mechanism of fabric influence on skin physiology to develop an understanding of the relationship between the fabric properties and skin physiology, as well as the established relationship between the exogenous and endogenous factors of clothing and skin physiology.

Chapter 6 studies the roles of fabric on skin physiology in hot environment with specific physiological activities such as resting, running, and recovering to understand the effects of clothing material, transfer behavior, and mechanical properties on skin physiology as well as human body thermal physiology.

Chapter 7 studies effects of UV blocking fabric on skin physiology under solar exposure to understand the role of fabric UV protection effects on skin physiology.

Chapter 8 summarizes the findings and discusses further work.

Chapter 2 Framework to Study the Effects of Clothing on Skin Physiology

2.1 Introduction

On the basis of the literature review comprising skin physiology and clothing effects delineated in the previous chapter (Chapter 1), in this chapter a theoretical framework is proposed to map potential interaction of clothing with skin from the following perspectives:

- physical-physiological,
- physical-psychological,
- physical-physiological-immunological, and
- neuropsychological-physiological.

A series of hypotheses are proposed on the potential mechanisms of the dynamic interaction between clothing and human physical, physiological, psychological, and immunological effects.

To verify these hypotheses, a systematic experimental approach has been adopted with careful consideration of the factors involving potential interaction in the framework.

2.2 Framework and hypotheses

The skin provides a physical barrier at the interface of human body with the external environment, to protect the human body against a range of noxious stressors such as temperature, electrolyte/fluid balance, mechanical, chemical, microbial, and UV radiation. Also, the skin accomodates the periphery's 'sensing' system. The skin and its appendages have been identified as both a source and a target of neuro-transmitters, neuro-hormones and neuro–peptides, although these aspects previously were domain of the central nervous system (Tobin 2005).

The bio compounds of the skin have ensured that skin physiology could be influenced by exogenous factors, such as environmental factors like moisture/humidity, temperature, air movement, and radiation (IR and UV), and endogenous factors, like human physiological and psychological status. Clothing can influence the exogenous factors by its physical properties. From the literature review, however, it also has become clear that clothing has significant impact on human physiological and psychological status. This suggests that clothing may influence skin by exacting both endogenous and exogenous effects.

On the basis of the literature review in Chapter 1, the framework below is proposed to illustrate the potential mechanisms relating to the interactions between clothing and skin physiology both endogenously and exogenously (Fig. 2-1).

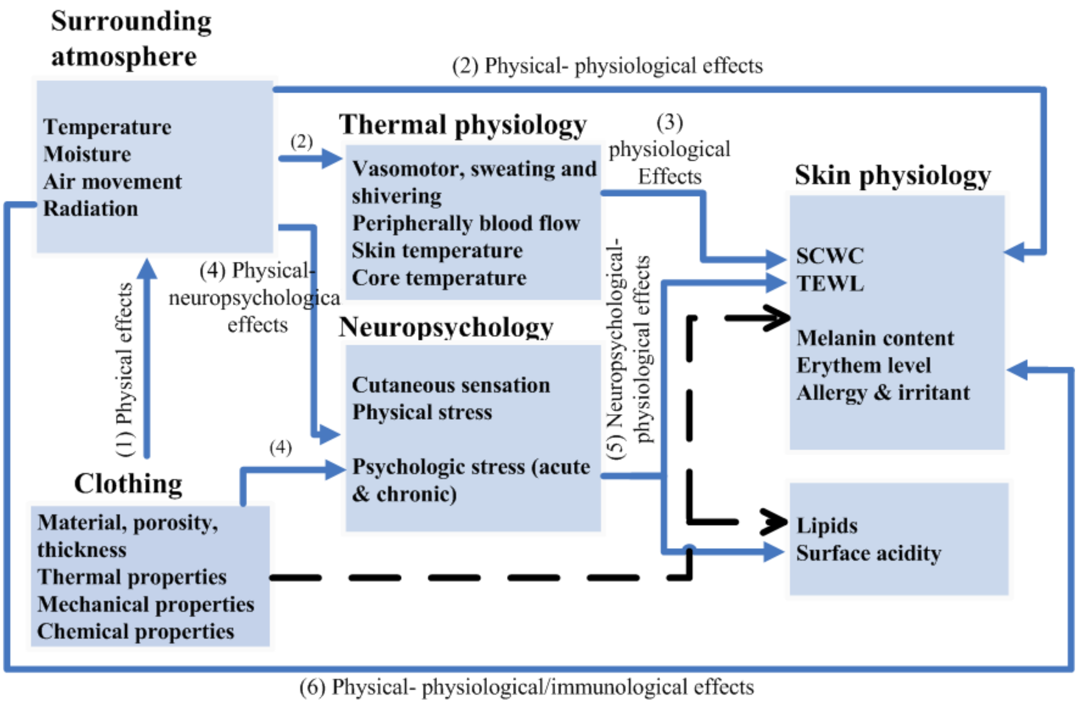


Figure 2-1 Effects of clothing on skin

The factors, that could conceivably influence skin and the interactions are summarized in Fig. 2-1, as: (1) physical effects of clothing on surrounding atmosphere of the skin; (2) physical-physiological effects of the environment; (3) physiological effects of thermal physiological responses to the environment; (4) physical-neuropsychological effects of environment and clothing on human cutaneous sensation, and stress; (5) psychological-physiological effects of neuropsychological responses to the environment and the properties of clothing; and finally, (6) physical-physiological/immunological effects of the environment and the properties of clothing. Let us look at these factors in some details.

2.2.1Physical effects of clothing on surrounding atmosphere of the skin

Clothing, the second skin, influences the environment surrounding the skin through its heat transfer, moisture/liquid water transport and air movement properties.

2.2.2 Physical-physiological effects of the environment on skin

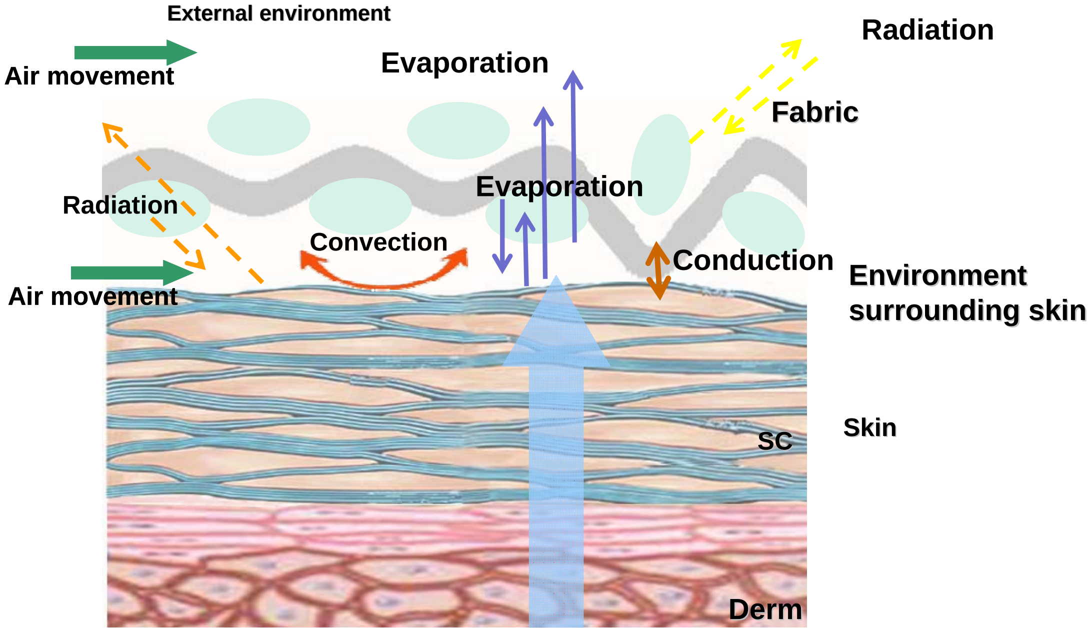


Figure 2-2 Physical-physiological effects on skin physiology

The physical-physiological effects presented in this section describe the influences of fabric physical properties on surrounding atmosphere of the skin, and the impact of these properties on skin physiology.

Skin is mainly composed of protein and lipids, including keratin, collagen, ceramides, cholesterol, free fatty acids and some small molecular weight water-soluble components. The small molecular weight water-soluble components, such as moisturizing factors (amino acids, urea, lactic acid and salts) can bind water, to keep the stratum corneum moisturised (Rawlings et al. 1994; Rawlings. 2003).

Regarding to the TEWL, the water from the intercellular spaces and corneocytes to the skin surface via diffusion and evaporation processes are significantly influenced by the surrounding atmosphere (Agache 2004; Pirot et al. 2004).

Previous studies have demonstrated that SCWC and TEWL can be influenced by environmental temperature (Spencer et al. 1975; Potts 1986), moisture/humidity (Halkier-Sorensen et al. 1995; Pirot et al. 2004), and air movement (Rycroft 1985; Barel et al. 1995; Cheng et al. 2008). Humidity of the environment influences the SCWC due to the capability of stratum corneum to bind with water (Potts 1986; Takenouchi et al. 1986). Stratum corneum water content may increase by 50% when the temperature is raised from 20 to 35 °C at a relative humidity 60% or below (Spencer et al. 1975).

TEWL reduces by almost 30% in animals maintained in dry (RH<10%) versus humid (RH: 80%) environments (Pirot et al. 2004). In fact it has been found that a positive relation exists between skin temperature and TEWL (Halkier-Sorensen et al. 1991; Halkier-Sorensen et al. 1991).

Air movement on the skin surface accelerates water evaporation and increases TEWL (Cheng et al. 2008). Exposure under wind for longer time induces lower stratum corneum water content in cold conditions. Air movement dehydrates the outer stratum corneum (Rycroft 1985; Barel et al. 1995).

In response to the dry and cold environment, thickness and dry weight of stratum corneum increases as a homeostatic response to counter excessive TEWL (Denda et al. 1998).

In steady status, without considering chimney and bellows effects of clothing, thermal properties of fabrics have considerable impact on heat and moisture/liquid water transfer and kinetics (hygroscopic property) between clothing and human body (Wang 2003; Li et al. 1993; Wong 2002). This implies that fabric may influence

SCWC and TEWL, due to its capability to influence the environment surrounding the skin (Fig. 2-2).

Apart from the above effects which are directly physical-physiological ones, physical effects on desquamation of keratinocytes in stratum corneum need to be highlighted (described in section 1.2.2). As mentioned earlier, a number of enzymes are present in the intercellular regions of the stratum corneum, such as Stratum Corneum Chymotryptic Enzyme (SCCE), Stratum Corneum Tryptic Enzyme (SCTE), Stratum Corenum Thiol Protease (SCTP) and aspartic protease Cathepsin D (Charalambopoulou et al. 2002; Caubet et al. 2004). These enzymes adjust the normal desquamation of keratinocytes in stratum corneum (Haftek 2003). As the activities of these enzymes can be influenced by water content and temperature (Steriotis et al. 2002), it is assumed that fabrics influence the renewal of stratum corneum due to its effect on surrounding atmospheres of the skin, then, impact on SCWC and TEWL. Based on this deduction, *hypothesis I* is proposed as:

Hypothesis I

Physical properties of clothing could impact on SCWC and TEWL due to biochemical properties of the skin that could be influenced by environmental surroundings in terms of temperature and humidity.

From the literature review of ‘Skin surface acidity (pH)’ in Chapter 1, it was noted that the histidine-to-urocanic-acid pathway is a major endogenous mechanisms influencing skin surface acidity, which is largely responsible for SCWC and TEWL (Rawlings et al. 1994; Harding et al. 2000). As proposed in *hypothesis I*, fabric could impact on SCWC and TEWL by influencing surrounding atmosphere of the skin, and thus it can be proposed that fabric property may impact on skin surface acidity (*hypothesis II*).

Hypothesis II

Clothing could influence skin surface acidity because of its effects on skin hydration.

2.2.3 Physiological effects of thermal physiology in hot environment

Heat balance in human body is achieved by heat exchange between human body and environment. Body heat exchange occurs through five physical processes: radiation, conduction, convection, evaporation and respiration (Silverthorn et al. c2004.). Vasomotor and sweating are the two major physiological mechanisms of heat loss (Cuergo 2008), which are mainly controlled by peripheral blood flow to adjust skin temperature as well as to regulate body core temperature.

In response to high environmental temperature, the body needs to take thermoregulatory actions such as accelerating peripheral blood flow to increase skin temperature which helps release heat from body to environment and once skin temperature approaches core temperature, evaporation of sweat from the skin surface cools the body thereby improving heat transfer from the core. Evaporation from skin provides the major defense against overheating. In hot weather, evaporation provides about 75% of total heat loss (Arens et al. 2006).

As discussed earlier, high intensity of evaporation will induce extended water exposure of stratum corneum, leading to extensive disruption of stratum corneum intercellular lipid lamellae, so that the epidermis become hydrated and corneocytes swell.

Clothing, with different air, moisture and liquid water transport properties, can influence both evaporation and conduction heat loss processes in the human body in hot environment. In turn, this makes it possible to impact on not only stratum corneum water content but also skin evaporation.

Based on the above understanding, hypotheses *III and IV* are proposed as:

Hypothesis III

Clothing may influence thermal physiology of human body in terms of core temperature and skin temperature in hot weather as it affects the evaporation and conduction heat loss in the human body.

Hypothesis IV

Clothing could influence water content of stratum corneum and skin evaporation in hot environment by influencing heat and moisture and liquid water transfer between human body and environment.

2.2.4 Physical-neuropsychological-physiological effects of environment on neuropsychological factors and skin physiology

From the literature review, it is clear that the nerve endings in skin tend to mediate sensations such as touch, pressure, heat cold, and pain, induce neuropsychological responses.

The skin is the interface between the external and internal environment and so it is critical to the maintenance of the constancy of the body's internal environment. The skin acts as a neuroendocrine organ in the periphery and is largely independent of control from the body's traditional and central stress system.

Clothing contacts most parts of the skin dynamically and frequently. This produces various thermal, mechanical, chemical or electric stimuli, and contributes to the perception of thermal and mechanical (tactile/prickle) sensations.

Fabric material, thickness, porosity, moisture regain, liquid water transfer behavior, and surface characters affect the thermal properties of fabric, such as thermal conductivity, absorption, thermal resistance, air permeability, thermal diffusion and stationary heat flow (Adam 1998; Hoffmann et al. 2001; Hatch 2005; H.J. Shim et al. 2003; Hatch et al. 2006).

Heat exchange occurs once clothing touches the skin. Clothing thermal properties influence skin physiology, neurophysiology, and psychology. Physicists have shown that thermal properties of fabric influence temperature and humidity in surrounding atmosphere of the skin (Yao et al. 2001). From the viewpoint of neurophysiology, thermoreceptors detect the skin temperature through the nerve endings (Zotterman 1953). Thermal sensitivity shows attributes of spatial and temporal summation thus increasing the area or the duration of the stimulus (Guyton 2006). The stimulus is converted into an action potential and then transferred from one neuron to another. The brain and nervous system receive inputs from the neuron then generate signal of heat or cold sensations (Guyton 2006).

Mechanical properties of fabric induce skin sensory reactions through multi-dimensional attributes of physical properties. In textiles factors like raw material, yarn structure, planar structure and finishing treatments affect the sensory response (MacKay et al. 1996; Hari 1997; Hu et al. 2006). Fabric physical properties such as thickness and weight, mechanical properties like extensibility, bending shear, and inplane compression properties, surface properties of compression, friction and surface irregularity influence the sensory properties of fabrics (Li 1988; Boos et al. 2005; Hu 2006; Hu et al. 1993; Wilson et al. 1995). In fact a study has found that people with atopic dry skin react more easily to mechanical irritation from fibers (Matthies 2003).

During wear, comfort sensation is closely related to fabric roughness, fullness, wettability, permeability, fabric perpendicular deformability, water vapor permeability, and thermal resistance of fabric. Hot sensation is correlated with thermal resistance; while cold sensation is correlated with wettability and thermal resistance of fabrics (Li 1988).

As summarized above, based on the interpretation of influence of thermal and mechanical properties of clothing on neuropsychological responses, we can argue that clothing may induce physical stress from thermal and mechanical attributes.

From the literature review in the 'Effects of stress on skin physiology' section, it is noted that hydration of facial skin in humans was impaired by both physical and psychological stress (Altemus et al. 2001), and psychological stress could influence stratum corneum barrier function (Altemus et al. 2001; Denda et al. 2000). These observations do suggest that clothing may impact on skin physiology by inducing physical stresses on human body. Hypothesis *V* is thus proposed as:

Hypothesis V

Clothing thermal/mechanical properties influence subjective thermal and mechanical sensations, which may induce physical stresses, stimulate the sympathetic nervous system, and thus influence SCWC and TEWL.

Based on the understanding of lipids of skin (section on the 'Lipids of skin' in Chapter 1), we understand that the lipids are produced during epidermal keratinocytes differentiation, and secreted from sebaceous glands. Stress has been demonstrated to induce a decrease in keratinocyte and an increase of sebaceous excretion (Gauthier 1996). It also has been proved by Gribanov (1999) and Aberg (2007) (Gribanov et al. 1999; Aberg et al. 2007), that skin lipids show a reaction with stress. Lipids of skin may be influenced by stress induced by clothing. The lipids of skin could further influence skin hydration as it has a role in skin barrier function. Therefore, hypothesis *VI* is proposed as:

Hypothesis VI

Clothing may influence skin lipids due to stresses induced by clothing and could further influence skin hydration. This could have an additional influence on skin surface acidity.

2.2.5 Physical-physiological/immunological effects on skin physiology

Effects of UV radiation on skin physiology have been presented in the literature. It is understood that solar exposure generally induces sun tan and inflammatory response, as well as erythema (Luger et al. 1990; Boelsma et al. 2001). Further, long time solar exposure induces epidermal thickening (Bech-Thomsen et al. 1993), and it has been demonstrated to increase the TEWL in hairless mice (Thiele et al. 2003).

Clothing is a simple and effective means of protecting the skin against UV radiation (Hanke et al. 1997; Rosen 1999; Achwal 2000; Saraiya et al. 2003; Dumitrescu et al. 2005; Hatch et al. 2006). The UV protection capability of clothing depends on garment style, fiber content and weave, fabric contracture, yarn and fabric porosity, cover factor, type, weight, thickness, moisture content, finishing agent (Adam 1998; Hoffmann et al. 2001; Hatch 2005; Hatch et al. 2006). Moreover, stretching, shrinkage, wetness, laundering, and wear of the fabric over time influence fabric UV blocking performance (Adam 1998; Bast et al. 1998; Hoffmann et al. 2001). The application of UV absorbers (optical whitening/brightening agents and UV-cutting agents) significantly improves the UV protection performance of a garment (Hoffmann et al. 2001; Goyal 2005).

Based on the above points, hypothesis *VII* is proposed as:

> ***Hypothesis VII***
>
> *UV blocking properties of clothing may influence SCWC, TEWL, skin melanin content, erythemal level and immunological response under acute solar exposure.*

2.3 Summary of hypotheses

After discussing relationships between clothing, surrounding atmosphere of the skin, thermal physiology, neuropsychology and skin physiology, the potential physiological interactions of clothing and skin as well as the potential mechanisms arising from these interactions are proposed as a series of hypotheses, which are summarized below:

Hypothesis I

Physical properties of clothing could impact on SCWC, TEWL due to physical and biochemical properties of the skin that could be influenced by surrounding environment in terms of temperature and humidity.

Hypothesis II

Clothing could influence skin surface acidity because of its effects on skin hydration.

Hypothesis III

Clothing may influence thermal physiology of human body in terms of core temperature and skin temperature in hot weather as it affects the evaporation and conduction heat loss of human body.

Hypothesis IV

Clothing, could influence water content of stratum corneum and skin evaporation in hot environment by influencing heat and moisture and liquid water transfer between human body and environment.

Hypothesis V

Clothing thermal/mechanical properties influence subjective thermal and mechanical sensations, which may induce physical stresses, stimulate sympathetic nervous system, and thus influence SCWC and TEWL.

Hypothesis VI

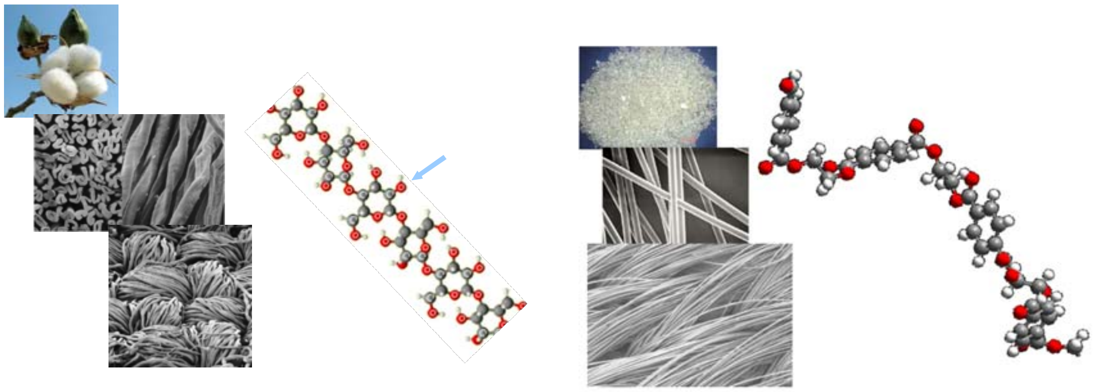
Clothing may influence skin lipids due to stresses induced by clothing and could further influence skin hydration. This could have an added influence on skin surface acidity.

Hypothesis VII

UV blocking properties of clothing may influence SCWC, TEWL, skin melanin content, erythemal level and immunological response under acute solar exposure.

2.3 Research Design

To verify the above hypotheses, factors are needed to be determined before the study is carried out. To clarify the effects of clothing on skin physiology in daily life, first of all, effects of fabric material on skin physiology will be the focus in this study. As hygroscopic properties play important role in heat and moisture transport between skin and clothing, it was selected as the first factor to be studied. Representing hygroscopic and non hygroscopic textiles, cotton and polyester are selected as fiber materials for this study.



Cotton
cellulose molecule source:
(http://www.biotopics.co.uk/JmolApplet/cellulosejdisplay.html)

Polyester
Polyester molecule source:
(http://www.swicofil.com/images/polyesterchain.gif)

Figure 2-3 Cotton and polyester and their molecules

Cotton and polyester are both made up of giant polymer molecules. Cotton is a naturally occurring polymer consisting of a long chain of glucose molecules (Fig. 2-3). There are OH groups on the outer edge, which provide a set of negatively charged groups. The water molecule, with its one oxygen atom attached to two hydrogen atoms, gives it a slightly positive charge, which is attracted by the negatively charged sites in the cotton fabric, making cotton absorb water well. So, cotton is a hygroscopic fiber. On the other side, polyester is synthesized from purified terephthalic acid (PTA) or its dimethyl ester dimethyl terephthalate (DMT) and monoethylene glycol (MEG). In its molecule there are a number of places where it can form bonds with water molecules, but not as many places as the cotton molecules. So, polyester can't bind with water as much as cotton, and is a weak hygroscopic fiber (called as weak hygroscopic fiber in this study).

To investigate the various effects of fabric on skin physiology, this study was designed to comprise three phases. Phase I has been designed to study effects of fabric on skin physiology within a specific environmental condition of mild cold, with temperature around 20 ºC (Chapter 3, 4 and 5). Phase II was designed to study the effects of fabric on skin physiology in hot environment, with the selected environmentalal condition of temperature 32 ºC and relative humidity 50% (Chapter 6). Phase III was designed to study the effects of fabric on skin physiology under UV, wear trial, which was carried out with solar exposure (Chapter 7).

Experimental clothing has been well controlled as cotton and polyester knitting fabrics with same yarn size and structure to eliminate extra influences except material. To enhance physiological response, fully covered long sleeve top and long pants pajama is selected as style of experimental clothing both in phase I and phase II of the study.

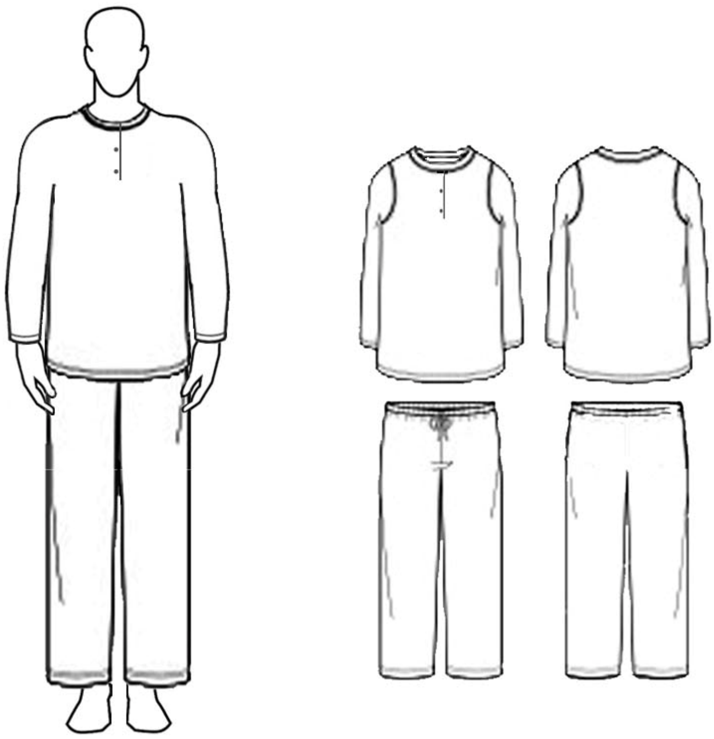


Figure 2-4 Style of experimental garments

Human physiological and neuropsychological responses are very sensitive to variations in exogenous factors (environment) and endogenous factors (personal physiological and psychological) variation. To eliminate the influences from external environment and emotional variation, sleep period is selected as experimental time (Fig. 2-4) in phase I. To elucidate the effects of fabric properties on skin physiology in our daily wear, period of wear trial was designed as three weeks that is required as the renewal time of stratum corneum. To study the effects of fabric on skin physiology, sensory responses, and urinary catecholamine were recorded and studied during the trials.

In phase II of the study, environmental temperature was controlled to 32 ºC and three activities were arranged as resting, running and recovering processes to ensure that sweat is generated in order to study the effects of fabric on skin physiology in hot environment.

Detail experimental designs for each area of the study will be introduced in relevant chapters.

Chapter 3 Effect of Pajama Thermal Properties on Stratum Corneum Water Content under Mild Cold Environment

3.1 Introduction

To achieve the second, third and fourth objectives of this study, the effects of fabric on skin physiology are clarified in this chapter. On the basis of literature review, we found that fabrics with different thermal properties could influence microclimate between skin and clothing, induce human physiological response through different thermal insulation. The change of microclimate and psychological action could influence skin physiological status. As mentioned above, based on understanding of biological characters of skin and its physiology, it is hypothesized (detail presented in Chapter 2) that:

Hypothesis I

Physical properties of clothing could impact on SCWC, TEWL due to physical and biochemical properties of the skin that could be influenced by surrounding environment in terms of temperature and humidity.

Hypothesis V

Clothing thermal/mechanical properties influence subjective thermal and mechanical sensations, which may induce physical stresses, stimulate sympathetic nervous system, and thus influence SCWC and TEWL.

These hypotheses were tested by conducting wear trials with human subjects who wore pajamas made from polyester and cotton fabric, which are the two most widely applied fibers in the market, representing hygroscopicity (hygroscopic and weak hygroscopic properties) of the two big segmentations in natural and synthetic fabric.

3.2 Methodology

The experimental protocol was approved by the Hong Kong Polytechnic University Human subjects ethics sub-committee. Ten healthy adult volunteers served as participants. They were nonsmokers and were not on any medications. They were fully informed of the methods and risks before consent was obtained.

The experiment was carried out from February to March in 2004 in Hong Kong. The weather conditions were recorded and the daily average temperature was 18.0 (±2.95ºC) and daily average relative humidity 78.5 (±7.27%) (Observatory 2004 a; Observatory 2004 b). All subjects wore cotton underwear. The volunteers were randomly divided into two groups (A and B). Each group consisted of three males and two females. The ten participants were aged between 23 and 42 years, with an average height of 169.1±7.99 cm, and an average body mass of 67.8±11.49 kg. There were no significant differences in age, height and body mass between groups A and B. They were asked to maintain a regular life style during the six weeks of the experimental period and were prohibited from smoking, drinking alcohol, performing heavy exercise and retiring later than normal hours. Participants were also prohibited from using body cream and/or glycerin on the body surface, except their face, hands and feet.

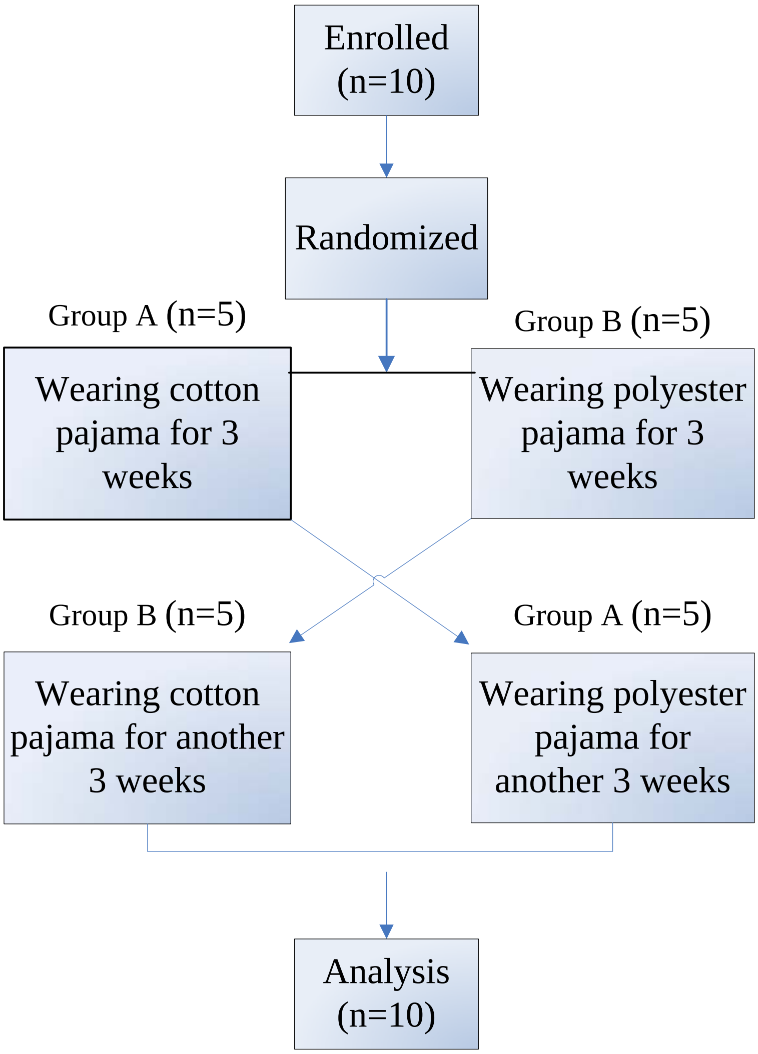


Figure 3-1 Study design

A parallel, cross-over, blinded wear trial has been conducted to investigate whether polyester and/or cotton fabric influence SCWC during daily wearing (Figure 3-1). In the first three weeks, group A wore cotton pajamas (95% cotton, 5% spandex) and group B wore polyester pajamas (95% polyester, 5% spandex). In the following three weeks, the two groups switched the clothing worn. The participants slept at night in a thermoneutral zone without the use of air-conditioning. They were asked to change from their own clothing into the experimental pajamas just before retiring.

During the daytime they wore their own clothing but all were required to wear cotton underwear.

Every Tuesday morning, the participants, wearing the pajamas, entered a climatic chamber controlled at a room temperature of 20±1ºC and a relative humidity of 55±5%. They rested for 30 minutes before the tests were conducted and then they completed two questionnaires relating to sleep quality and subjective perception. The Pittsburgh Sleep Quality Index (PSQI) (Buysee D. J et al. 1989) was used to obtain information on the participants' sleep quality. Another questionnaire assessed the participants' subjective perception of *overall comfort* while wearing the pajamas. The SCWC was measured by Skicon 200EX (Hamamatsu, Japan) (Tagami H et al. 1980; Fluhr et al. 1999; Fluhr et al. 1999); in the region of the central back area of the spinal column from T4 to T6. Measurements were completed ten times for each subject.

Urinary free catecholamines were tested in order to know stress level during sleep under the influence of different materials for the pajamas.

3.3 Materials

3.3.1 Experimental pajamas and their physical properties

Two kinds of fabrics were selected for pajamas in this experiment. One was 95% cotton, 5% spandex, and the other was 95% polyester, 5% spandex. Both fabrics used 32s yarn, and were knitted in double face. The physical properties of the two kinds of pajamas fabrics are summarized in Table 3-1. The polyester fabric is significantly thicker and heavier than the cotton fabric. Polyester has substantially lower moisture regain (i.e. lower moisture sorption capacity) and significantly lower thermal conductivity, but much higher thermal diffusivity than the cotton fabric, showing that the polyester fabric is much less absorbent and bigger volumetric heat capacity fabric than the cotton fabric even though it is thicker and heaver.

Table 3-1 Physical properties of the two kinds of pajama fabrics

Properties	**Cotton fabric pajama** (95% cotton 5% spandex)	**Polyester fabric pajama** (95% polyester 5% spandex)
Weight (mg/cm^2)	16.80±0.03	19.27±0.05
Thickness (mm)	0.73±0.02	0.83±0.02
Moisture regain (%)	5.90±0.13%	0.84±0.13%
Thermal conductivity (W/cm^2/°C)±	0.64±0.02	0.54±0.01
Air resistance (Kpa*s/m)	0.01±0.00	0.07±0.00
Water vapor permeability (g/m^2/24hr)	750.93±39.35	713.71±41.94
Moisture management property index	36.30±22.63	727.26±432.74
Thermal diffusivity (cm^2/s)	0.26#	0.42#

Note: # calculated results

3.3.2 Questionnaires

Subjective sensations were obtained from a questionnaire by rating the six sensations (*dampness*, *coldness*, *itchiness*, *softness*, *breathable*, and *overall comfort*) on an eleven points scale at the early morning on the day of testing (Appendix I).

The Pittsburgh Sleep Quality Index (PSQI) (Buysee D. J et al. 1989) was used to obtain the quality and pattern of sleep in this experiment (Appendix II). The PAQI is an assessment tool to measure sleep quality and disturbances by self-rated questionnaire. Nineteen individual items generate seven component scores, including subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. The sum of these seven scores yields one global score (global Sum). The global score of ‘5’ or greater indicates a ‘poor’ sleeper.

3.3.3 Measurements

The equilibrium moisture content (regain) of the clothing materials was measured according to standard ASTM 2495. Thermal conductivity was measured by KES-F7 THERMO LABOII (Kato Tech. Co.). The SCWC was measured by Skicon 200EX. (Skicon 200EX IBS Company, Hamamatsu, Japan) (Tagami H et al. 1980; Fluhr et al. 1999; Fluhr et al. 1999). Urinary free catecholamines (adrenaline, noradrenaline, and dopamine) was measured by high performance liquid chromatography with electrochemical detection HPLC-ECD (EiCom, Japan) (Volin 1994). Overnight urine was collected in polyethylene containers, with 1.5 ml of 6N hydrochloric acid (preservative) added to 50ml urine. Samples were stored at -80°C. Separation was performed by column EICOMPAK CA-5ODS (2.1mmID x 150mm). Mobile phase contained 88% 0.1M phosphate buffer pH6.0, 12% methanol (HPLC, 99.9% Aldrich), and 600mg/L sodium octanesulfonate (Aldrich), 50mg/L EDTA.2Na. Flow rate is 0.23ml/min. Standards Adrenaline, noradrenaline, dopamine, dehydroxy benzylamine (DHBA, internal standard, Sigma) were obtained from Sigma (St. Louis, Mo. USA).

3.3.4 Statistics

Stratum corneum water content and catecholamines data are presented as means ± std. The data has been transformed to distributed normality if necessary. Subjective perception and sleep quality are present as middle (maximum-minimum). T-test and Mann-Whitney test were performed to analyze the data. Repeated Measure-ANOVA (clothing x time) was used to evaluate whether fabric (material) and wearing time (time) influence SCWC. These ANOVAs compared within-subject SCWC. Hierarchical linear regression (HLR) was performed to analyze the relationship among subjective perception of pajama materials, sleep quality and SCWC. The influence of fabric materials and sleep quality was studied as categorical variable. Pajamas material 'cotton' and sleep quality 'good' were regarded as reference categories. Variables with a univariate significance level of <0.05 were included in the model. A 2-tailed p value of <0.10 was considered to be significant. All data were analyzed statistically using SPSS 12 (Statistics Package for the Social Sciences).

3.4 Results

3.4.1 SCWC

The mean value of the SCWC just before the acclimatization period was 164±30 microSiemens for the cotton fabric pajamas and 162.8±74 microSiemens for the polyester fabric pajamas. These values were not significantly different (n=10, t=0.1, P=0.961). The mean value of the SCWC in the 3rd week was 342±66 microSiemens for the cotton fabric pajamas and 188±89 microSiemens for the polyester fabric pajamas. The values were significantly different (n=9, t=3.0, P=0.02). During the 3-week trial, SCWC on the skin of the back of participants who had worn cotton pajamas was significantly higher than that of participants who had worn polyester pajamas (n=28, t=5.0, p<0.001). Mean values over the whole of the 6 weeks was 276±93 microSiemens in the group wearing cotton pajamas and 199±76 microSiemens in the group wearing pajamas made of polyester (Fig. 3-2). The results indicated that the SCWC in cotton group is significantly higher than the SCWC in polyester group (n=65, t=3.3, P=0.002).

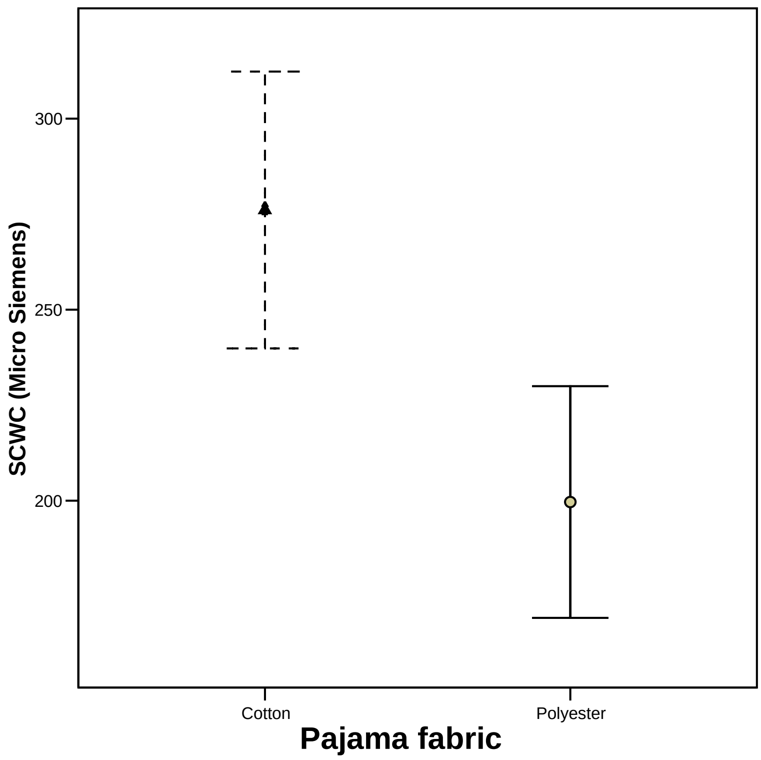


Figure 3-2 A comparison of mean SCWC between two groups.
SCWC in cotton group is significantly higher than polyester group (n=65, t=3.3, P=0.002)

As shown in Fig. 3-3(a) below, the SCWC increased more markedly over weeks 1-3 with the cotton than the polyester fabric pajamas (n=28, t=4.3 P=0.000). As shown in Fig. 3-3(b), the SCWC of the participants who wore the cotton fabric pajamas in the first three weeks decreased markedly during fourth week and gradually increased, but was below the values obtained in the first three weeks when wearing the polyester fabric pajamas in the second three weeks. On the other hand, the SCWC of the subjects who wore the polyester fabric pajamas in the first three weeks fell slightly during first week and then increased steadily when wearing the cotton pajama in the second three weeks. It should be noticed that a marked fall of 112±21 microSiemens was observed when participants changed from cotton to polyester pajamas after the third week, compared with the fall of 40±78 microSiemens when the change was in the opposite direction. The difference was highly significant (n=10, t=5.4, p=0.001).

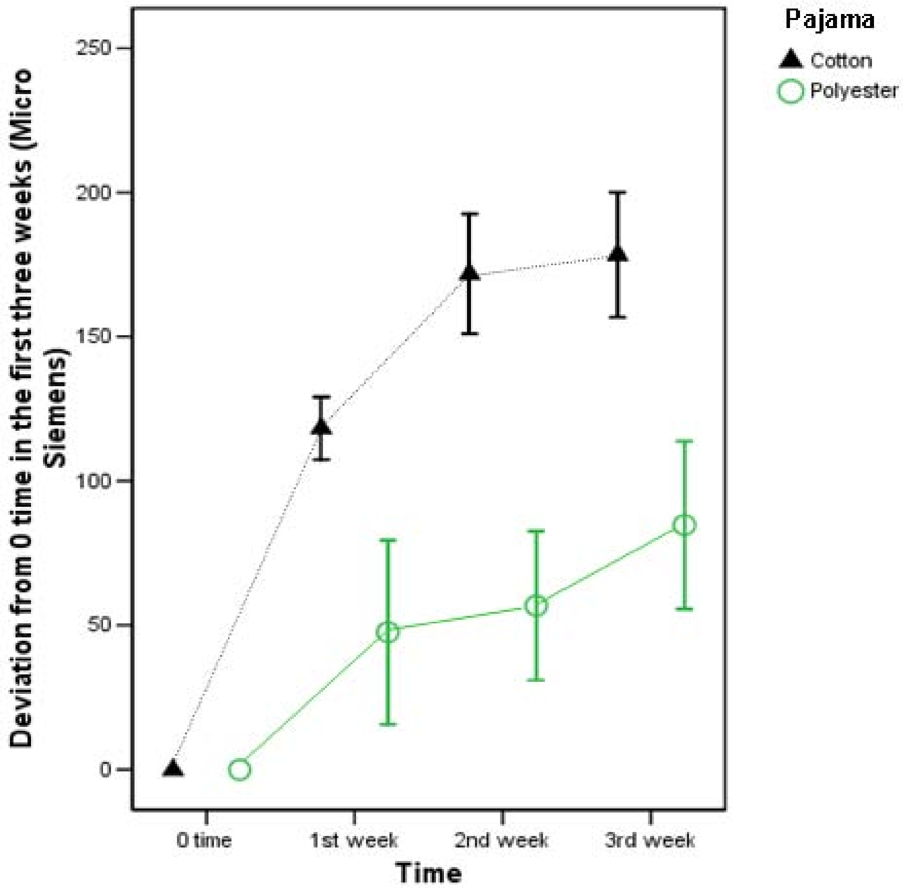


Figure 3-3 (a) Temporal changes of mean SCWC in the first three weeks.
The SCWC data before wear trial as benchmark. The changes of SCWC for each group were significantly different (p=0.000).

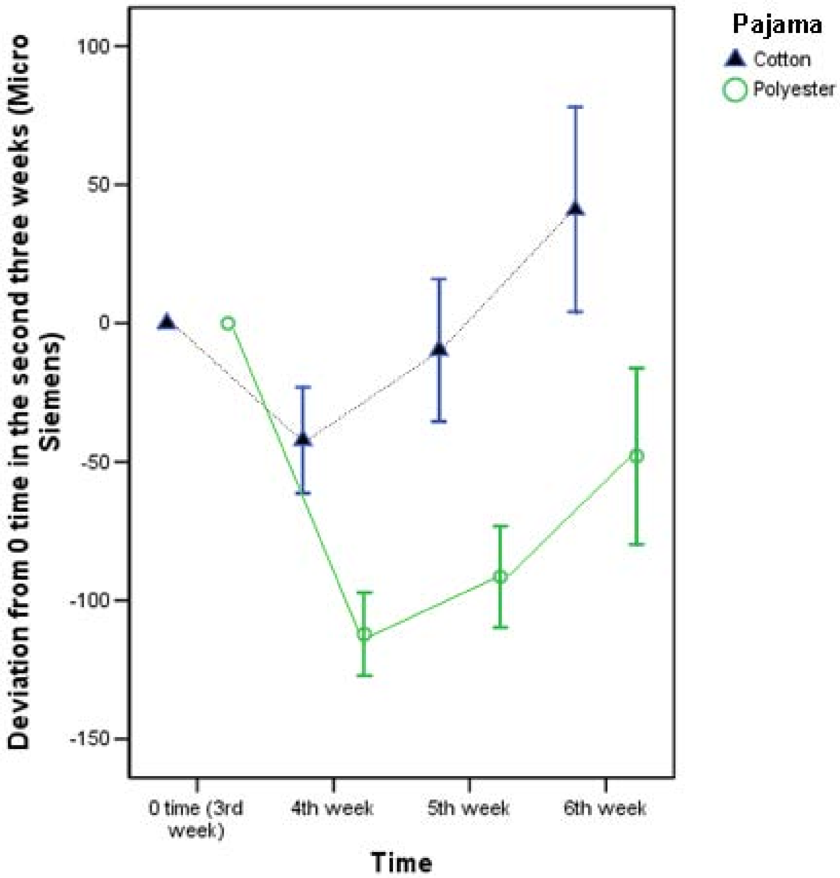


Figure 3-3 (b) Temporal changes of mean SCWC in the second three weeks. The SCWC data in third week as benchmark. The changes of SCWC for each group were significant different (p=0.000).

Table 3-2 Effects of pajama material and time on SCWC

Tests of Within-Subjects Effects						
Source		**Type III Sum of Squares**	**df**	**F**	**Sig.**	
Time	Greenhouse-Geisser	15980.195	1.260	1.280	0.294	
Pajama	Sphericity Assumed	2531.567	1.000	1.212	0.299	
Time * Pajama	Sphericity Assumed	52803.033	2.000	11.438	0.001	***

Repeated Measure analysis shows that both Time and Pajama material have no significant effect on SCWC, while a significant Time by Pajama interaction effect (F=11.438, p<0.001) is noted (Table 3-2). This suggests that there is not any single effect of pajama material or time on SCWC, but a more complex mechanism, with an interaction of duration of wearing the different material pajama, was evident. This implies that physiological response of skin may involve in this complicity.

3.4.2 Subjective perception

The different pajama fabric had no significant effect on subjective perceptions, such as *damp, itchy, softness, breathable*, and *overall comfort.*[1] However, the results indicate that there is a significant difference between cotton and polyester pajama on subjective thermal perception of *warmness* - (n=58, u=-2.230, p<0.05). Subjects feel colder when wearing polyester pajamas compared with wearing of cotton pajamas.

3.4.3 Sleep quality

Among the cotton and polyester groups, there was no significant difference in terms of subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, daytime dysfunction, and global sum, the sleep quality index[2]. Test results indicated that pajamas materials have no significant effect on sleep quality.

3.4.4 Catecholamines

The overnight urinary catecholamines in cotton group was 331.99±196.58nmol, and was 474±230.80nmol in polyester group. Test results indicated that overnight urinary

[1]Both Mann-Whitney test and T-test have been applied to study the effects of pajama fabric on subjective perception. The t-test results indicated that pajama fabric has an effect on subjective perception of *coldness* (n=58, t=2.4, p=0.02). However, the distribution of the subjective perception data did not follow normality. Furthermore, its measurement is ordinal, so we report the Mann-Whitney test results in this chapter.

[2] Both Mann-Whitney test and T-test have been used to study the effects of pajama fabric on sleep quality. The results indicated that pajama fabric had not significant affected sleep quality by both methods. However, the distribution of the data did not follow normality. And, its measurement is ordinal, so we chose to report the Mann-Whitney test results here.

free catecholamines tended to be higher in the polyester group than in the cotton group (n=28, t=-1.89, p=0.071) during the experimental period.

3.4.5 Influence of pajamas materials on SCWC

HLR has been performed to evaluate the relation among pajamas materials, environment, perception of *coldness* and *overall comfort*, sleep quality, catecholamines, and SCWC. The table of correlation matrix shows the Pearson correlation and the significance of each variable (Table 3-3). SCWC correlated with pajamas materials, subjective perception of *coldness*, and with *overall comfort* significantly at the 0.05 level or at higher levels; SCWC did not correlate with environmental temperature, relative humidity and sleep quality. Subjective perception of *coldness* and *overall comfort* correlated with pajamas materials (p<0.05); and sleep quality correlated with perception of *coldness* and *overall comfort* (p<0.05)

Table 3-3 Correlations between SCWC and other variables

Correlations						
Pearson Correlation	1	2	3	4	5	6
1 SCWC on back						
2 Pajamas(cotton=0)	-0.38**					
3 Coldness	-0.45**	0.31*				
4 Overall comfortable	0.29*	-0.29*	-0.35**			
5 Temperature (ºC)	-0.01	0.05	-0.14	0.06		
6 Relative humidity(%)	0.07	0.00	-0.03	-0.01	-0.03	
7 Sleep quality (good=0)	-0.07	0.10	0.40**	0.29*	-0.14	-0.02

*p<0.05, **p<0.01, ***p<0.000

The results of the hierarchical linear regression to predict change in SCWC over 3-week period are presented in Table 3-4. Fabric materials of pajamas and subjective perception of *coldness* were two strong predictors of SCWC at 3 weeks. Polyester pajamas have a negative effect on SCWC compared with cotton pajamas (reference variable). Additionally, perception of *coldness* also has a negative effect on SCWC. Subjective perception of *overall comfort*, environmental factors such as temperature and humidity, and sleep quality were not significant predictors of SCWC. Model 2 was selected to describe the relation between SCWC, pajamas, and subjective perception of *coldness*. The model 2 has the relatively higher R^2, and it could explain 26.3% of dependent variable of SCWC.

Table 3-4 Regression models

		Coefficients			Model summary			
Model		Standardized Coefficients Beta	t	Sig.	R square	F change	Sig. F Change	
1	Pajama(cotton=0)	-0.38	-2.89	0.01	0.141	8.360	0.006	**
2	Pajama(cotton=0)	-0.26	-2.03	0.05	0.263	8.295	0.006	**
	Coldness	-0.37	-2.88	0.01				
3	Pajama(cotton=0)	-0.24	-1.83	--	0.271	0.561	--	
	Coldness	-0.34	-2.54	0.01				
	Comfortable	0.10	0.75	--				

a Dependent Variable: SCWC on back

3.5 Discussion and conclusions

The wear trial described above has clarified the effects of fabric on skin physiology in mild cold weather. Wearing different material pajamas for three weeks significantly influences SCWC, while, it also influences subjective *coldness* sensation, and stress level (over night free urinary catecholamines).

SCWC level of the skin is significantly higher when the pajama with high moisture regain (cotton) is worn. The influence of clothing on SCWC is not induced by the fabric material only, but also induced by an interaction by time (duration of wearing the garment). It suggests that there is not just a simple physical effect involved, but probably a more complex physiological effect may play a role in the process. The higher SCWC may improve the activity of the number of enzymes present in the intercellular regions of the stratum corneum, SCCE, SCTE, SCTP and Cathepsin D (Charalambopoulou et al. 2002; Caubet 2004), and such activity adjusts the renewal of the SC, not only sustaining the regular renewal of the SC in mildly cold condition, but also keeping the skin moisten and fresh.

It is indicated that subjects felt warmer when wearing the cotton fabric pajamas due to its lower thermal diffusivity, while felt colder wearing polyester fabric due to its higher thermal diffusivity. The cotton fabric would reduce the intensity of stimulation to cold receptor under mildly cold conditions. On the other hand, wearing polyester pajamas with higher thermal diffusivity, the fabric would reduce its temperature more quickly, and then the cold receptors in skin surface might have been stimulated more intensively, thus eliciting skin sympathetic nerve activity, and furthermore, activating the sympathetic nervous system, which would result in a decrease of SCWC. Skin sympathetic nerve activity plays an important role on skin SCWC as it is sensitive to thermal stimuli, and may regulate peripheral vasoconstriction (Cogliati et al. 2000).

The sympathetic nervous system was reported to be more active under the influence of non-hydroscopic, low hydrophilic textile materials (Ha et al. 1996; Kwon et al. 1998), and this was evidenced by the findings that heart rate was significantly higher when weak hygroscopic and low hydrophilic clothing like polyester, rather than hygroscopic and highly hydrophilic clothing (high moisture regain and high liquid water absorption), like cotton, was worn during intermittent exercise in a warm environment.

The 'Sleep quality' is a control factor, which inspects any influence from sleep quality on skin physiology in this wear trial. It was show that there is no significant different in term of Sleep quality between cotton and polyester group. It helps to make conclusion that skin physiology can be influenced by clothing material, but not from sleep quality in this wear trial.

The experimental results show that the higher the moisture sorption capacity and the lower the thermal diffusivity of the clothing materials, the higher the level of SCWC in the skin, which illustrates the physical-physiological effects of fabric on skin physiology. Further analysis by the HLR has indicated the relationship among pajamas materials, subjective perception of *coldness* and SCWC. The results have verified the hypothesis *I* and *V* proposed in Chapter 2 as:

- *Physical properties of clothing* ***impact*** *on SCWC due to the fact that* ***physical and biochemical properties*** *of the skin can be influenced by surrounding environment in terms of temperature and humidity.*
- *Clothing thermal properties* ***influence*** *subjective thermal sensation, which* ***stimulate*** *sympathetic nervous system and* ***induce*** *physical stress, and then, influence SCWC.*

Chapter 4 Influence of Fabric Water Transport Properties on Stratum Corneum Hydration under Mildly Cold Environment

4.1 Introduction

In chapter 3, effects of fabric material pertaining to hypothesis *I* and *II* have been clarified. From examining the effects of fabric material hygroscopic properties on skin physiology in mildly cold conditions (Yao 2006; Yao et al. 2006; Yao et al. 2007), I found that wearing cotton pajamas during nocturnal sleep induced higher SCWC, perception of warmth and lower catecholamines level compared with wearing polyester pajamas. Polyester fabric had a negative effect on SCWC compared with cotton.

Not only do the hygroscopic properties of fabric influence microclimate temperature and humidity, but also the ability of liquid water absorption properties (hydrophilicity) influence microclimate condition. The different moisture/liquid water absorption properties of fabric, such as hydrophilicity (liquid water absorption) and hygroscopicity (moisture absorption) could interact and modify the heat regulating function of the skin.

Hygroscopicity is the capability of a fabric to absorb moisture from surrounding environment (mainly from air) (Anon 1913), which can be measured by moisture present in a material, expressed as a percentage of the dry weight, and is called as moisture regain, as determined under definite prescribed conditions (Anderson 1976).

Cotton fabric could be regarded as a hygroscopic fabric with relatively higher moisture content (around 6.8% at 20ºC and 60% relative humidity), while polyester could be regarded as weak-hygroscopic (or very weak hygroscopic) fabric with lower moisture content (around 0.9% in 20 ºC and 60% relative humidity). Hydrophilicity is the affinity of a fabric for liquid water (Hu et al. 2005). The hydrophilicity level of fabric can be characterized by the contact angle of liquid water on fabric surface. The higher the contact angle (over 90˚) the more hydrophobic the fabric.

As the ability of water and moisture absorption of polyester fabric is lower than cotton fabric, to clarify whether these differences were caused by hydrophilicity or hygroscopicity of the pajamas, this experiment was designed and conducted to investigate associations between hydrophilicity and hygroscopicity of fabrics and skin physiology in this study to verify the hypothesis *I*, *II*, *V* and *VI*.

Hypothesis I

Physical properties of clothing could impact on SCWC, TEWL due to physical and biochemical properties of the skin that could be influenced by surrounding environment in terms of temperature and humidity.

Hypothesis II

Clothing could influence skin surface acidity because of its effects on skin hydration.

Hypothesis V

Clothing thermal/mechanical properties influence subjective thermal and mechanical sensations, which may induce physical stresses, stimulate sympathetic nervous system, and thus influence SCWC and TEWL.

Hypothesis VI

Clothing may influence skin lipids due to stresses induced by clothing and further could influence skin hydration. This could have an added influence on skin surface acidity.

4.2 Methods

The experimental protocol was approved by the Hong Kong Polytechnic University Human Subjects Ethics Sub-committee. Thirty two healthy adult volunteers served as participants. They were nonsmokers and were not on any medications. They were fully informed of the methods and risks before consent was obtained.

The experiment was carried out from February to March in 2005 in Hong Kong. The weather conditions were recorded to show a daily average temperature 16.0 (±1.7ºC) and daily average relative humidity 81.8 (±5.9%) (Observatory 2005 a; Observatory 2005 b). All subjects wore cotton underwear starting a week before the wear trial. The thirty two volunteers were divided into four groups (hydrophilic cotton, hydrophobic cotton, hydrophilic polyester and hydrophobic polyester), each group contained four male and four female volunteers. The physiology data of the volunteers in each group is summarized in Table 4-1. They were asked to adhere to a regular life style during the six weeks of the experimental period and were prohibited from smoking, drinking alcohol, performing heavy exercise and retiring later than normal. Participants were also prohibited from using body cream and/or glycerin on the body surface, except their face, hands and feet. The volunteers slept at night in a thermal neutral zone without the use of air-conditioning. They were asked to change from their own clothing into the experimental pajamas just before retiring. During the daytime they wore their own clothing with cotton underwear.

The volunteers, wearing the pajamas, entered a climatic chamber controlled at a room temperature of 20±1ºC and a relative humidity of 50±5%. They rested for 30 minutes before the test were conducted and completed questionnaire the questionnaire known as The Pittsburgh Sleep Quality Index (PSQI) (Buysee D. J et al. 1989). The SC water content and TEWL were measured in the region of the central back area of the spinal column from T4 to T6. Measurements were made four times for each subject.

Table 4-1 Physical characteristics of the volunteers

Groups	Hydrophilic cotton	Hydrophobic cotton	Hydrophilic polytester	Hydrophobic polyester
Age (Mean±STD)	30.46±5.86	31.50±5.96	31.00±7.49	30.13±7.03
Hight(cm)(Mean±STD)	168.22±7.63	150.20±7.91	164.25±5.52	161.81±8.19
Weight (Kg)(Mean±STD)	69.29±21.29	64.94±15.97	57.21±9.56	56.25±10.16

Over night urinary noradrenaline (OUNE) (Fox 2006) was tested in order to know activity of sympathetic nervous system during sleep under the influence of different materials of pajamas. Overnight urine was collected in polyethylene containers, with 1.5 ml of 6N hydrochloric acid (preservative) added to 50ml urine. Samples were stored at -80°C. Separation was performed by column EICOMPAK CA-5ODS (2.1mmID x 150mm). Mobile phase contained 88% 0.1M phosphate buffer pH6.0, 12% methanol (HPLC, 99.9% Aldrich), and 600 mg/L sodium octanesulfonate (Aldrich), 50 mg/L EDTA.2Na. Flow rate is 0.23 ml/min. Standards noradrenaline, and dehydroxy benzylamine (DHBA, internal standard) were obtained from Sigma (St. Louis, Mo. USA).

4.3 Materials

4.3.1 Experimental pajamas and their physical properties

Four kinds of fabrics were prepared to make the pajamas which would be used in this experiment. Cotton fabric (32s yarn, knitted in double face, 95% cotton, 5% spandex) was selected as a hygroscopic fabric, and polyester (32s yarn, knitted in double face, 95% polyester, 5% spandex) as a weak hygroscopic fabric. Both the cotton and polyester fabrics were treated, to have four fabrics with different moisture transport properties namely hydrophilic and hydrophobic cotton fabrics (hygroscopic), and hydrophilic and hydrophobic polyester fabrics (weak hygroscopic).

The basic physical properties of the four kinds of pajamas fabrics are summarized in Table 4-2. The hydrophobic polyester fabric is significantly thicker than the other fabrics. Polyester (hydrophilic and hydrophobic) has substantially lower moisture regain (i.e. lower moisture sorption capacity) and significantly lower weight, but much higher thermal diffusivity than the cotton fabric, showing that the polyester fabric is less absorbent than the cotton fabric. Water vapor permeability in cotton fabrics is significantly higher than in polyester fabrics, implying that cotton fabrics is much easy transport skin evaporation through the fabric than polyester. Table 4-2 presents that air resistance in cotton fabrics is significantly higher than in polyester fabrics, showing that air exchange in cotton fabrics is weaker than polyester fabrics.

Table 4-2 Physical properties of the four pajamas fabrics

Note: ***: p<0.000

4.3.2 Measurements

Skin physiological parameters, SC water content was measured by Corneometer® CM 825 (CK electronic, Germany); TEWL was measured by Tewameter® TM 300 (CK electronic, Germany). Another important index of skin barrier function, sebum, was also measured by photometric method (electronic 2005; Sunwoo et al. 2006), and applied Sebumeter® SM 815 (CK electronic, Germany). Skin surface acidity has been measured by Skin-pH-Meter® PH 905 (CK electronic, Germany). Overnight urinary catecholamines were measured by high performance liquid chromatography with electrochemical detection HPLC-ECD (EiCom, Japan) (Volin 1994).

4.3.3 Questionnaires

Subjective sensations were obtained from the questionnaire shown in Appendix I on an eleven points scale at the early morning of testing day.

The Pittsburgh Sleep Quality Index (PSQI) (Buysee D. J et al. 1989) was applied to obtain the quality and pattern of sleep in this experiment. Details have been introduced in Chapter 3.

4.3.4 Statistical analysis

Data of SC water content was transformed by base-e logarithm function (LnSCWC), and overnight urinary noradrenaline (OUNE) was transformed by square root function to achieve normality. Skin physiological and hormonal data (LnSCWC, TEWL, skin surface acidity, sebum, overnight urinary free catecholamines, and SQRTOUNE) are presented as mean±std. Statistical analysis was performed using Univariate with Post-hoc analyses module in SPSS 12 to investigate the association between hydrophilicity, hygroscopicity and SC water content as well as TEWL. Further, t-test was applied to compare differences once association was found. Association and differences were considered significant when $P < 0.05$. Subjective perception and sleep quality are present as middle (maximum-minimum) and Kruskal-Wallis Test were performed to analyze the data.

4.4 Results

The summary of skin physiological and physiological characteristics is listed in Table 4-3. Their comparisons results are shown in Table 4-4.

Table 4-3 Summary of physiological characteristics

Pajama	Hydrophobic cotton	Hydrophilic cotton	Hydrophilic polytester	Hydrophobic polyester	F	Sig.	
TEWL(g/cm^2/h) (Mean±STD)	5.55±1.34	5.51±1.42	4.87±1.28	4.81±1.53	2.89	0.04	*
SCWC(Microsiemens) (Mean±STD)	217.79±69.41	212.98±71.58	171.60±73.60	209.95±106.78	3.01	0.03	*
Sebum	8.94±6.60	6.86±7.68	10.43±6.43	10.51±6.43	1.77	0.16	
Skin surface acidity (pH)	5.01±0.33	4.95±0.26	4.98±0.37	5.00±0.28	0.38	0.77	
NE(pmol) (Mean±STD)	32.03±27.54	40.86±23.81	38.43±28.31	51.35±32.27	2.09	0.10	
Catecholamines (pmol) (Mean±STD)	480±233	542±225	553±263	548±227	1.08	0.36	

Table 4-4 Comparisons of physiological characteristics

Multiple Comparisons (LSD)

Dependent Variable:		TEWL			LnSCWC		
(I) Pajama	(J) Pajama	Mean Difference (I-J)	Sig.		Mean Difference (I-J)	Sig.	
Hydrophobic cotton	Hydrophilic cotton	0.044	0.913		-0.006	0.960	
	Hydrophilic polytester	0.686	0.091		0.291	0.019	*
	Hydrophobic polyester	0.741	0.079		0.090	0.473	
Hydrophilic cotton	Hydrophobic cotton	-0.044	0.913		0.006	0.960	
	Hydrophilic polytester	0.642	0.121		0.297	0.018	*
	Hydrophobic polyester	0.697	0.105		0.096	0.448	
Hydrophilic polyester	Hydrophobic cotton	-0.686	0.091		-0.291	0.019	*
	Hydrophilic cotton	-0.642	0.121		-0.297	0.018	*
	Hydrophobic polyester	0.054	0.898		-0.201	0.113	
Hydrophobic polyester	Hydrophobic cotton	-0.741	0.079		-0.090	0.473	
	Hydrophilic cotton	-0.697	0.105		-0.096	0.448	
	Hydrophilic polytester	-0.054	0.898		0.201	0.113	

Dependent Variable:		Sebum			pH	
(I) Pajama	(J) Pajama	Mean Difference (I-J)	Sig.		Mean Difference (I-J)	Sig.
Hydrophobic cotton	Hydrophilic cotton	2.081	0.289		0.126	0.179
	Hydrophilic polytester	-1.491	0.468		0.101	0.279
	Hydrophobic polyester	-1.565	0.429		0.071	0.439
Hydrophilic cotton	Hydrophobic cotton	-2.081	0.289		-0.126	0.179
	Hydrophilic polytester	-3.572	0.081		-0.025	0.789
	Hydrophobic polyester	-3.646	0.065		-0.054	0.552
Hydrophilic polyester	Hydrophobic cotton	1.491	0.468		-0.101	0.279
	Hydrophilic cotton	3.572	0.081		0.025	0.789
	Hydrophobic polyester	-0.074	0.971		-0.030	0.745
Hydrophobic polyester	Hydrophobic cotton	1.565	0.429		-0.071	0.439
	Hydrophilic cotton	3.646	0.065		0.054	0.552
	Hydrophilic polytester	0.074	0.971		0.030	0.745

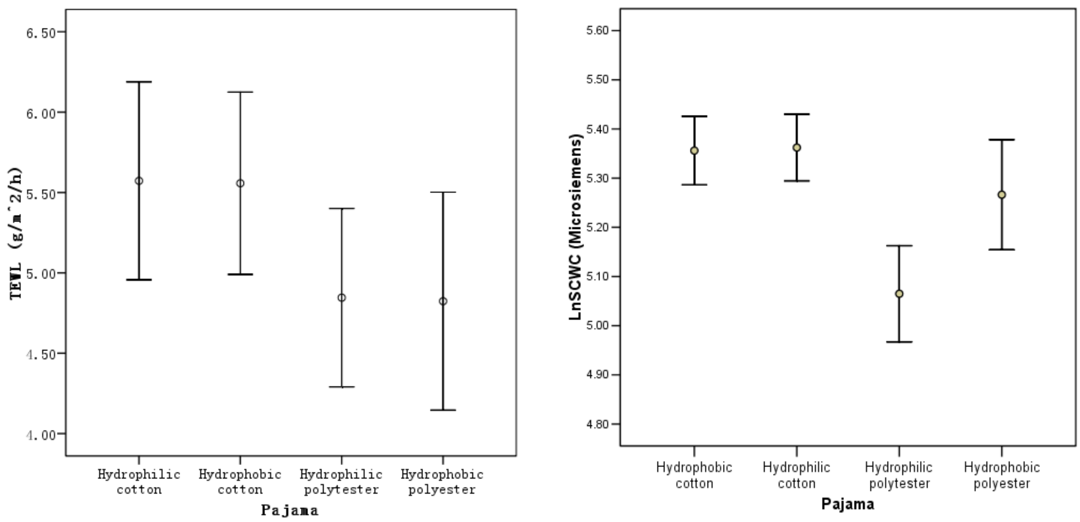
Dependent Variable:		SQRTOUNE			Catecholamines	
(I) Pajama	(J) Pajama	Mean Difference (I-J)	Sig.		Mean Difference (I-J)	Sig.
Hydrophobic cotton	Hydrophilic cotton	-1.550	0.001	***	-61.407	0.325
	Hydrophilic polytester	-1.099	0.026	*	-72.932	0.243
	Hydrophobic polyester	-1.705	0.001	***	-67.957	0.291
Hydrophilic cotton	Hydrophobic cotton	1.550	0.001	***	61.407	0.325
	Hydrophilic polytester	0.450	0.354		-11.525	0.857
	Hydrophobic polyester	-0.155	0.742		-6.551	0.921
Hydrophilic polyester	Hydrophobic cotton	1.099	0.026	*	72.932	0.243
	Hydrophilic cotton	-0.450	0.354		11.525	0.857
	Hydrophobic polyester	-0.605	0.219		4.974	0.940
Hydrophobic polyester	Hydrophobic cotton	1.705	0.001	***	67.957	0.291
	Hydrophilic cotton	0.155	0.742		6.551	0.921
	Hydrophilic polytester	0.605	0.219		-4.974	0.940

Note：* $p<0.05$, ***$p<0.001$

4.4.1 Stratum corneum hydration

The mean and standard deviation of TEWL and LnSCWC in the experimental period covering three weeks are presented in Figure 4-1 (a) and (b). The comparisons of TEWL and LnSCWC have been summarized in Table 4-3. TEWL in hydrophobic cotton group tends to be higher than polyester groups (p<0.1). However, there is no significant difference between hydrophilic cotton group and polyester groups. Post-hoc analysis shows that LnSCWC in hydrophilic polyester group is significantly lower than hydrophilic and hydrophobic cotton groups (p<0.05).

Associations between fabric hydrophilicity/hygroscopicity properties and skin hydration are shown in Table 4-5. Hygroscopicity of pajamas has a significant association with LnSCWC (p<0.05, F=5.02) and TEWL (p<0.05, F=5.81). However, hydrophilicity of pajamas has no significant association with skin hydration. There is no significant association from hydrophilicity and hygroscopicity interaction.



(a) **(b)**

Figure 4-1 Skin hydration TEWL (a) and LnSCWC (b)

Table 4-5 Associations between pajamas fabric hydrophilicity, hygroscopicity and skin hydration

Skin hydration	Source	df	F	Sig.	
LnSCWC					
	Hydrophilicity	1	1.61	0.21	
	Hygroscopicity	1	5.02	0.03	*
	Hydrophilicity * Hygroscopicity	1	1.36	0.25	
TEWL					
	Hydrophilicity	1	0.00	0.96	
	Hygroscopicity	1	5.81	0.02	*
	Hydrophilicity * Hygroscopicity	1	0.00	0.95	

Note: * $p<0.05$

Further, t-test results show that there is no significant differences pertaining to LnSCWC and TEWL between hydrophilic and hydrophobic cotton groups. Similarly, there is no significant difference in terms of LnSCWC and TEWL in hydrophilic and hydrophobic polyester groups (Table 4-6). Hydrophilicity has no significant effect on skin hydration.

Table 4-6 Difference between hydrophilic and hydrophobic cotton/polyester groups

		t	Sig. (2-tailed)
Hydrophilic and hydrophobic cotton group			
	LnSCWC	-0.09	0.93
	TEWL	0.00	1.00
Hydrophilic and hydrophobic polyester group			
	LnSCWC	-1.47	0.15
	TEWL	0.09	0.93

4.4.2 Skin surface acidity (pH)

Skin surface acidity of the subjects ranged from 4.20 to 5.71, which is slightly acidic. Statistical analysis results show that both hydrophilicity and hydroscopicity of fabric have no significant effect on skin surface acidity, and there is no significant difference between the four groups. (Table 4-4 and Table 4-7)

Table 4-7 Effects of hydrophilicity and hygroscopicity of fabric on skin surface acidity

Tests of Between-Subjects Effects Dependent Variable: pH			
Source	df	F	Sig.
Hydrophilicity	1	0.548	0.461
Hygroscopicity	1	0.130	0.720
Hydrophilicity * Hygroscopicity	1	1.429	0.235

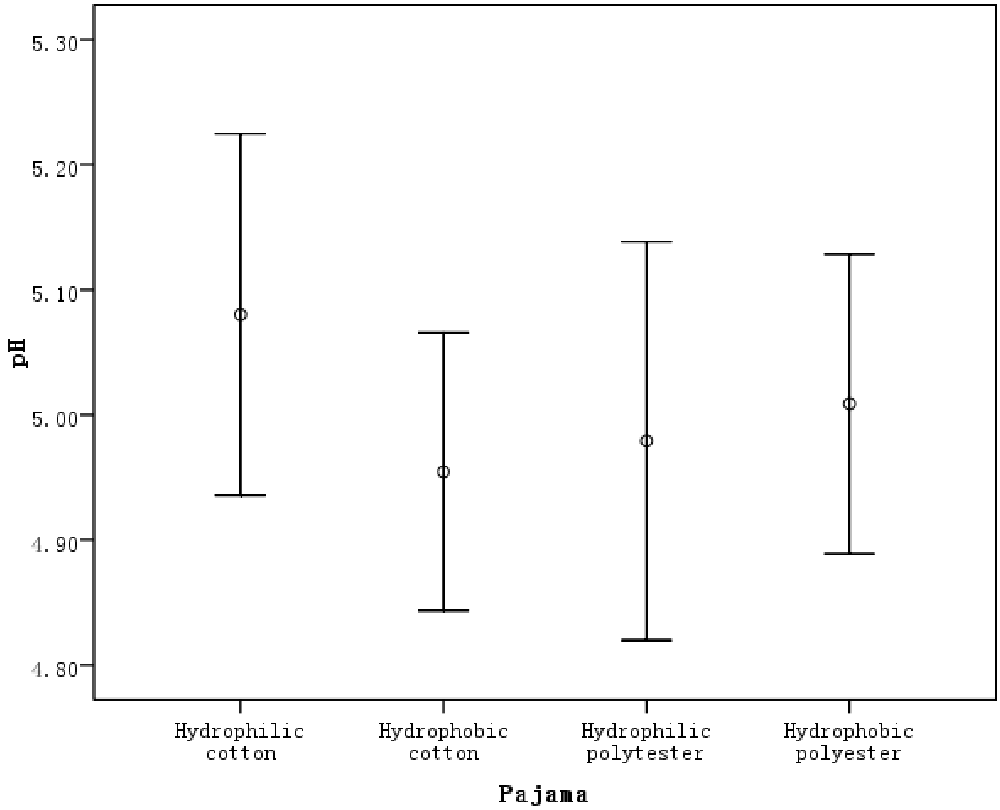


Figure 4-2 Skin surface acidity (pH)

4.4.3 Sebum

Sebum measured from all subjects ranged from 1 to 24.33, which belong to less sebum or dry skin type (electronic 2005).

Table 4-8 Effects of hydrophilicity and hygroscopicity of fabric on sebum

Tests of Between-Subjects Effects Dependent Variable: Sebum			
Source	df	F	Sig.
Hydrophilicity	1	0.504	0.479
Hygroscopicity	1	3.305	0.073
Hydrophilicity * Hygroscopicity	1	0.581	0.448

Analysis of results indicate that hygroscopicity of fabric tends to significantly affect skin sebum (F=3.305, p=0.073), but hydrophilicity has no significantly effects on sebum (Table 4-8). Sebum in hydrophobic cotton groups seems lower than other groups, but it is not statistically significant (Fig. 4-3). Sebum in hydrophilic cotton group is slightly lower than polyester groups (hydrophilic (p=0.081) and hydrophobic polyester (p=0.065) groups) (Table 4-4).

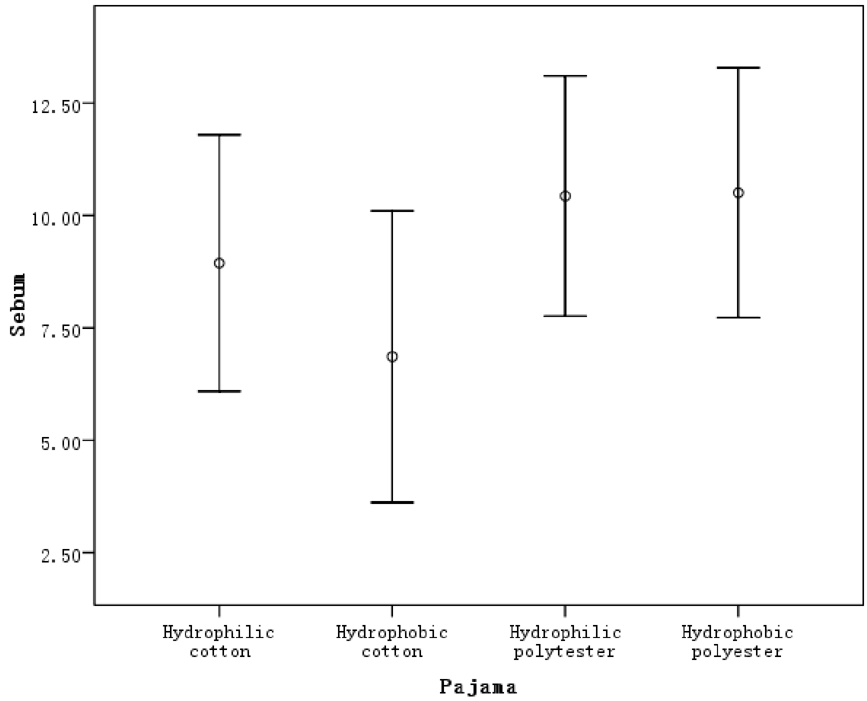


Figure 4-3 Sebum

4.4.5 Subjective sensation

The different pajama fabric had no significantly effect on subjective perceptions, such as *prickly, softness, breathable*, and *overall comfort*, except thermal (n=83, h=8.563, 3d.f., p=0.036) and damp (n=83, H=8.667, 3d.f., p=0.034) [3] sensations. Subjects felt warmer in hydrophobic groups than in hydrophilic groups; they reported a feeling of easy breathablility in cotton pajamas than in polyester groups.

4.4.6 Sleep quality

Among the cotton and polyester groups, there was no significance difference in terms of subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, daytime dysfunction, and global sum, the sleep quality index. Test results indicated that pajamas materials have no significant effect on sleep quality.

4.4.7 Catecholamines

The detail results of overnight urinary free catecholamines are illustrated in Fig. 4-4 (a-b). Statistical analysis shows that there is significant difference in the SQRTOUNE (F=5.463, p<0.05) but no significant different in overnight urinary free catecholamines (F=1.755, p=0.162) among the four groups. SQRTOUNE in hydrophobic cotton group is significantly lower than other groups. Univariate analysis (Table 4-9) indicated that hydrophilicity and hygroscipicity has a significant

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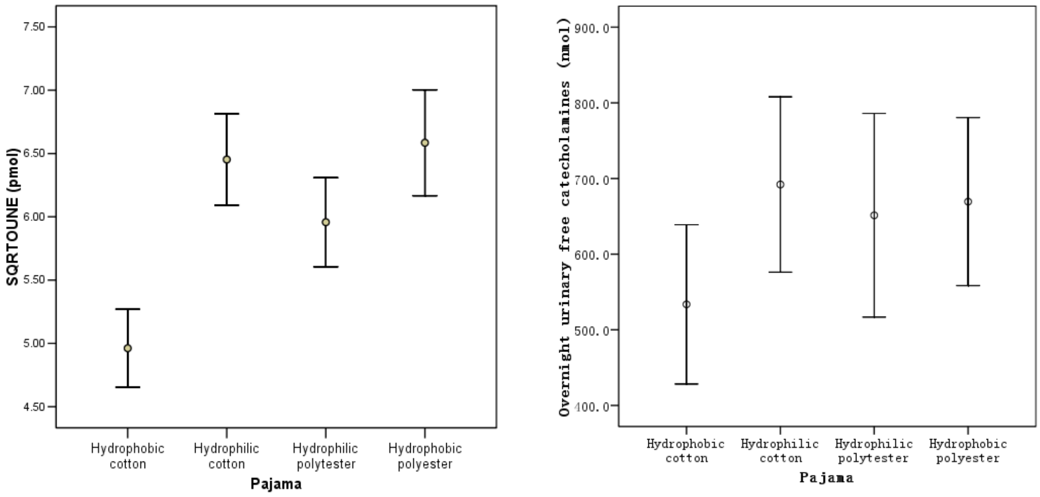
[3]Both Kruskal-Wallis Test and ANOVA have been applied to study the effects of pajama fabric on subjective perception. The ANOVA analysis results have indicated that pajama fabric affected subjective perception of *coldness* (f=2.70, p=0.050), and *damp* (f=2.742, p=0.049). Because of distribution of the subjective perception data did not follow normality, and its measurement is ordinal, so we report the Kruskal-Wallis Test results here.

interactional association with SQRTOUNE (p=0.001). Hydrophilicity of fabric tends to influence overnight urinary free catecholamines, meanwhile, hydrophilicity and hygroscipicity has a significant interactional association with overnight urinary free catecholamines (p<0.05).



Overnight urinary NE　　　　Overnight urinary free catecholamines

Figure 4-4 Overnight urinary free catecholamines

Table 4-9 Effects of pajama fabric on catecholamines

Tests of Between-Subjects Effects					
Dependent variable:		**df**	**F**	**Sig.**	
SQRTNE	Hydrophilicity	1	2.252	0.136	
	Hygroscopicity	1	2.570	0.112	
	Hydrophilicity*hygroscipicity	1	10.545	0.002	**
Catecholamines	Hydrophilicity	1	3.922	0.051	
	Hygroscopicity	1	0.380	0.539	
	Hydrophilicity*hygroscipicity	1	4.596	0.035	*

4.5 Discussion

The significant association between hyrophilicity properties of fabric and SCWC/ TEWL indicated that hygroscopicity of cotton fabric could be a key factor influencing stratum corneum during daily wearing. The reason could be water vapor content on the interface of skin and microclimate (skin and clothing) was higher when wearing hygroscopic fabric (cotton) clothing than wearing weak hygroscopic (polyester) clothing in steady state (Yao 2006). With higher water vapor content, more water molecule is in stratum corneum/microclimate interface, which could be absorbed by natural moisturized factors (such as ceramides, amino acids, sebaceous oils, urea, and so on) and keratin in SC would maintain the SC water content.

Meanwhile, differences in fabric properties, higher water vapor permeability of cotton fabric indicated that skin evaporation was much easy to transport through cotton fabrics than polyester fabric, might enhance TEWL. And higher air resistance and lower thermal diffusivity of cotton fabric implied air and heat exchange in cotton fabrics is weaker than polyester fabrics, which may keep the skin surface warmer in cotton groups in mildly cold condition. In addition, above influence could activate the enzymes such as (Corneum Chymotryptic Enzyme (SCCE), Stratum Corneum Tryptic Enzyme (SCTE), Stratum Corenum Thiol Protease (SCTP) and aspartic protease Cathepsin D) in SC, which play important roles in the process of proteolysis of the corneodesmosomal proteins, and thus promoting the process of SC desquamation (Lundstrom et al. 1994; Bernard et al. 2002; Bernard et al. 2002; Caubet 2004). The present study was designed and conducted in such a way that the wear trial duration was 3 weeks, which is close to period of SC renewal (26-40 days) (Ryan 1991). The design makes it possible to investigate the influence on the enzymes activity and involvement of the stratum corneum renewal process.

From the literature review, it was found that endogenous mechanisms play an important role on skin surface acidity, such as the histidine-to-urocanic-acid pathway (Ananthapadmanabhan et al. 2003). Histidine-to-Urocanic acid pathway is largely responsible for SC hydration (Rawlings et al. 1994; Harding et al. 2000). In the cornification process, filaggrin undergoes proteolysis to free amino acids, urocanic acid, pyrrolidone carboxylic acid, and ornithine/citrulline/aspartic acid, which make up much of the osmotically active material that largely accounts for the ability of the stratum to remain hydrated (Scott et al. 1986). Enzymatic processes of nonoxidative histidine deamination have been identified as contributing to stratum corneum acidification (Krien et al. 2000). However, in this wear trial, there is no significant effect of fabric on skin surface acidity. This may arise from the histidine-to-Urocanic acid pathway which does not provide the single explanation for the acidity of the skin. There are others pathways contributing to skin acidity, such as phospholipid-to-Free fatty Acid pathway. The products of this pathway is a pool of free fatty acids, which not only the influence the normal stratum corneum acidification, but also play an important role in the dual functions of stratum corneum integrity and cohesion (Fluhr et al. 2001). This is helpful to interpret the influence of fabric on sebum which mainly consists of free fatty acid.

There are reports that the acidity in skin surface also could be influenced by sweating (Freudenrich 2006). However, this wear trial carried out under 20 ºC, can’t activate the occurrence of sweating, so, this mechanism is absent in this trial.

The significant difference of OUNE among the four kinds of pajamas groups indicated that wearing pajamas of different materials during sleep could influence the sympathetic nervous system activity. Moisture regain of fabric could influence heat and moisture transfer between the body, clothing and the surrounding environment (Li et al. 2000; Li et al. 2004). It is probable that this may have caused the individual to become more stressed, suggesting that sympathetic nervous activity would be higher.

Hatch et al. have reported that water content in fabric could influence TEWL, and higher water content increase the TEWL (Hatch et al. 1992). Hatch explained that TEWL was influenced by the ability of the fabric to accumulate transepidermal water so that the mechanism leads to swelling of the stratum corneun under higher moisture content of the fabric (over 40% w/w) in local area and in short time (less than 60 minutes). From this study, it argues that not only swelling mechanism could influence the stratum corneum hydration, but more complex mechanisms, such as activation of sympathetic nervous system and stratum corneum biological renewal, could be involved.

The hygroscopic (moisture regain) property of the clothing material has significant influence in stratum corneum hydration.

4.6 Conclusions

From this experiment, hypotheses I, II, V and VI are verified as stated below:

- *Physical (moisture/liquid water transport) properties of clothing could impact on SCWC, TEWL due to physical and biochemical properties of the skin can be influenced by surrounding environment in terms of temperature and humidity.*
- *Clothing could not influence skin surface acidity.*
- *Clothing thermal/mechanical properties **influence** subjective thermal and mechanical sensations, which **stimulate** sympathetic nervous system and induce physical stress, and thus influence SCWC and TEWL.*

- *Clothing **tends to influence** skin lipids due to stress induced by clothing worn and further could influence skin hydration.*

Chapter 5 Mechanisms of Effects of Clothing on Skin Physiology under Mildly Cold Environment

5.1 Introduction

In chapter 3 and 4, effects of fabric hygroscopicity and hydrophilicity on skin physiology have been studied. From two wear trials, series of hypotheses have been verified. It is demonstrated that fabric hygroscopic property impacts on skin hydration, coldness perception, stimulate sympathetic nervous system during wearing pajamas made of different materials, and tends to influence skin lipids. The next question is: what's the role of physical properties of fabric? To better understand the mechanism of the influence of fabric on skin physiology, statistical method is applied to explore the potential mechanisms of the fabric properties that have an influence on skin physiology in mildly cold condition.

To establish a sound statistical framework, three aspects were considered to build up the relationship. The first is the fabric thermal and mechanical properties; the second is the neuropsychological parameters such as subjective sensation and stress level; the third is skin physiological parameters.

In this chapter, first, factors analysis is applied to abstract variables from measured physical properties, including transport properties (thermal conductivity, water vapor permeability, air vapor permeability), mechanical properties (shearing and tensile, compression, surface properties, and bending), and moisture transfer properties (moisture management properties). Then, Hierarchical Linear Regression (HLR) and logistic regression were applied to explore the relationship between these aspects to find potential mechanisms of influence of fabric on skin physiology. A framework describes the relationship between the skin physiology and fabric properties that has been established.

5.2 Method

Data base obtained from wear trial presented in Chapter 3 and 4 was used in this analysis. Details of experimental conditions have been described in earlier chapters. The pajamas fabric properties have been evaluated in terms of basic physical properties (thickness, weight), thermal properties (thermal conductivity, water vapor permeability, air vapor permeability), mechanical properties (shearing and tensile, compression, surface properties, and bending), and moisture transfer properties (moisture management properties). The following methods were applied to measure the relevant properties of the fabric:

a) Fabric weight--STM D 3776-85

b) Fabric thickness--STM D1777-96

c) Air permeability--KES-F8-API Air Permeability Tester (THERMO LABOII (Kato Tech. Co. Japan))

d) Thermal conductivity--Thermolab KES-FB7 (THERMO LABOII (Kato Tech. Co. Japan))

e) Fabric liquid water transport property --Overall moisture management capacity (OMMC)--Moisture Management Tester (Hu et al. 2005)

f) Mechanical properties --KES FB1, FB2, FB3, and FB4 (Kato Tech. Co. Japan).

The fabric properties were classified into a few factors by factor analysis to reduce variables, including thermal properties, liquid water transport properties and mechanical properties. SPSS Data Reduction function was applied to check and confirm the classification.

Hierarchical linear regression (HLR) was performed to analyze the relationship among factors pertaining to properties of pajamas, subjective perception, and skin physiology, as well as stress. The influence of fabric materials and sleep quality was studied as categorical variables. The basic assumptions underlying this test were also examined (i.e., normality and homogeneity of variance). Pajamas material, in terms of ‘hygroscopic’, and ‘hydrophilic’, as well as sleep quality ‘good’ were regarded as reference categories. Logistic regression was applied to explore the factors that influence the sleep quality. Variables with a univariate significance level of $p \leq 0.05$ were included in the model. A 2-tailed p value of <0.05 was considered to be significant. All data were analyzed statistically using SPSS 12 (Statistics Package for the Social Sciences).

5.3 Results

5.3.1 Factors analysis of fabric physical properties

Physical properties measurement has been performed following methods listed in section 5.2. The measurement results have been presented in Chapter 3 (Table 3-1), Chapter 4 (Table 4-2) and Appendix III and IV. Applying factor analysis, these physical properties have been used to obtain variables related to fabric thermal properties and mechanical properties.

Thermal properties

Table 5-1 Correlation of fabric thermal properties

Correlation Matrix				
	Correlation	1	2	3
1	Thermal diffusivity (cm^2/s)			
2	Air resistance (KpaS/m)	-0.38***		
3	Thermal condactivity (W/m/°C)	-0.30***	-0.61***	
4	Water vapour permeability (g/m^2/h)	-0.49***	-0.59***	0.90***

Note: ***: $p<0.001$

Table 5-2 Factor loadings of fabric thermal properties

Rotated Component Matrix(a)		
	Component	
	1	2
Water vapour permeability (g/m^2/h)	0.95	
Thermal condactivity (W/m/°C)	0.95	
Air resistance (KpaS/m)	-0.78	0.60
Thermal diffusivity (cm^2/s)		-0.97
Eigenvaluse	2.46	1.39
% of variance explained	61.44	34.71
Cumulative % of variance explained	61.44	96.15

Two factors were extracted from the four fabric physical properties (Table 5-2). The first factor 'Transport capability' included three items, accounting for 61.44% of the variance, which represents properties of water vapor, air, and heat transportation through the fabric. The second factor 'Thermal diffusivity' included one time, accounts of 34.71% of the variance, which indicates the ratio of the thermal conductivity to the volumetric heat capacity.

Mechanical properties

Table 5-3 Correlation of fabric mechanical properties

Correlation Matrix(a)																
Correlation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1 LT(-)																
2 WT(N/m)	0.94***															
3 RT(%)	0.88***	0.81***														
4 EMT(%)	0.88***	0.99***	0.73***													
5 G-MEAN(N/m/deg)	-0.22***	-0.50***	0.06***	-0.62***												
6 2HG-MEAN(N/m)	0.39***	0.10***	0.61***	-0.05***	0.81***											
7 2HG5-MEAN(N/m)	0.21***	-0.07***	0.49***	-0.21***	0.89***	0.98***										
8 B-MEAN(x 10-4 Nm/m)	0.93***	0.90***	0.81***	0.85***	-0.23***	0.30***	0.14***									
9 2HB-MEAN(x 10-2 N/m)	0.96***	0.91***	0.85***	0.85***	-0.17***	0.38***	0.22***	0.99***								
10 LC	-0.65***	-0.80***	-0.73***	-0.82***	0.49***	-0.00***	0.09***	-0.53***	-0.54***							
11 WC(N.m/m2)	-0.37***	-0.56***	-0.61***	-0.60***	0.34***	0.03***	0.05***	-0.39***	-0.36***	0.86***						
12 RC(%)	-0.99***	-0.89***	-0.88***	-0.81***	0.10***	-0.49***	-0.32***	-0.89***	-0.94***	0.58***	0.28***					
13 TM(x10-3 m)	0.89***	0.82***	1.00***	0.74***	0.06***	0.61***	0.49***	0.84***	0.88***	-0.71***	-0.59***	-0.89***				
14 T0(x10-3 m)	0.91***	0.73***	0.90***	0.62***	0.20***	0.73***	0.59***	0.82***	0.88***	-0.45***	-0.21***	-0.95***	0.91***			
15 MIU	0.34***	0.60***	0.31***	0.70***	-0.72***	-0.49***	-0.54***	0.52***	0.42***	-0.61***	-0.74***	-0.20***	0.31***	0.01***		
16 MMD	-0.20***	-0.14***	-0.36***	-0.09***	-0.15***	-0.38***	-0.36***	0.15***	0.04***	0.49***	0.24***	0.25***	-0.32***	-0.29**	0.35***	
17 SMD	-0.68***	-0.48***	-0.89***	-0.36***	-0.50***	-0.90***	-0.83***	-0.59***	-0.66***	0.41***	0.34***	0.74***	-0.89***	-0.89***	0.11***	0.43***

Note: ***: $p<0.001$

Table 5-4 Factor loadings of fabric mechanical properties

Rotated Component Matrix(a)			
	Component		
	1	2	3
LT(-)	0.96		
WT(N/m)	0.90		
RT(%)	0.84		
EMT(%)	0.84		
G-MEAN(N/m/deg)		0.94	
2HG-MEAN(N/m)		0.92	
2HG5-MEAN(N/m)		0.95	
B-MEAN(x 10-4 Nm/m)	0.99		
2HB-MEAN(x 10-2 N/m)	1.00		
LC	-0.51		0.81
WC(N.m/m2)			0.78
RC(%)	-0.94		
TM(x10-3 m)	0.86		
T0(x10-3 m)	0.88		
MIU		-0.77	
MMD			0.76
SMD	-0.65	-0.67	
Eigenvaluse	8.7	4.61	2.76
% of variance explained	51.15	27.11	16.24
Cumulative % of variance explained	51.15	78.26	94.5

The factors of the loading of the seventeen mechanical properties on the three factors were extracted. The first factor 'Elastic properties' included nine items, accounting for 51.15% of the variance, which mainly indicates the fabric elastic characters under extension and bending. The second factor 'Shearing resistance' included five items, accounting for 27.11% of the variance, which shows the fabric performance under shearing, and surface roughness. The third factor ‘Compressibility’ includes three items, accounting for 16.24% variance, which includes properties of fabric compressional resilience, linearity in compression and mean deviation in the frictional force.

5.3.2 Effects of pajamas fabric on subjective comfort perception

Hierarchical Linear Regression (HLR) has been performed to evaluate the relation among the physical properties of pajama fabrics and subjective comfort perceptions.

<u>*Coldness*</u>

Table 5-5 Correlation of *coldness* with fabric properties

Correlations						
	Pearson Correlation	1	2	3	4	5
1	Coldness					
2	Hydrophilicity (hydrophilic=0)	-0.20*				
3	Hygroscopicity (hygroscopic=0)	-0.18*	0.00			
4	Transport capability	-0.12	-0.41***	0.86***		
5	OMMC	0.13	-0.71***	0.49***	0.56***	
6	Shearing resistance	0.12	-0.92***	0.03	0.52***	0.35***

Note: *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$

Table correlation matrix in Table 5-5 shows the Pearson correlation and the significance of each variable (Table 5-5). Subjective coldness perception correlated with pajama fabric hydrophilicity and hygroscopicity properties significantly ($p<0.05$). Pajamas fabric hydrophilicity significantly correlated with fabric transport capability, differential wetting properties, compressibility and overall moisture management capacity (OMMC), while shearing resistance ($p<0.05$); fabric hygroscopicity significantly correlated with fabric transport capability, differential wetting properties, and OMMC ($p<0.05$).

Table 5-6 Model summary_*coldness*

Model		Coefficients			Model summary			
		Standardized Coefficients Beta	t	Sig.	R aquare	F change	Sig. F change	
1	Hydrophilicity (hydrophilic=0)	-0.20	-1.95	0.05	0.04	3.80	0.05	*
2	Hydrophilicity (hydrophilic=0)	-0.20	-1.97	0.05	0.07	3.30	0.01	**
	Hygroscopicity (hygroscopic=0)	-0.18	-1.82	0.07				
a	Dependent Variable: Coldness							

Note: *: p<0.05; **: p<0.01

The results from the HLR to predict subjective *coldness* perception are shown in Table 5-6. Pajama fabrics' hydrophilicty and hygroscopicity were the two strong predictors of subjective coldness perception. Compared with hydrophilic pajamas fabric, hydrophobic fabric has a negative effect on coldness perception. Compared with weak hygroscopic fabric (polyester), hygroscopic fabric (cotton) has a negative effect on coldness perception. Model 2 was selected to describe the relationship between subjective coldness perception and pajamas fabrics' physical properties.

Overall comfort

Table 5-7 Correlation of overall comfort with fabric properties

Correlations					
	Pearson Correlation	1	2	3	4
1	Overall comfort				
2	Transport capability	0.78***			
3	Compressibility	0.06	-0.15*		
4	Shearing resistance	0.00	0.12	0.00	
5	OMMC	0.27***	0.16*	0.12	0.20**

Note: *: p<0.05; **: p<0.01; ***: p<0.001

Table 5-7 shows correlation matrix of the Pearson correlation and the significance of each variable. Subjective overall comfort perception correlated with pajama materials transport capability and overall moisture management capacity (p<0.05). Pajamas fabric transfer properties significantly correlated with fabric compressibility and overall moisture management capacity (OMMC) (p<0.05). Fabric shearing resistance significantly correlated with overall moisture management capacity (p<0.05).

Table 5-8 Model summary_*overall comfort*

Model		Coefficients			Model summary			
		Standardized Coefficients Beta	t	Sig.	R aquare	F change	Sig. F change	
1	Transport capability	0.78	15.79	0.00	0.61	249.33	0.00	***
2	Transport capability	0.81	16.78	0.00	0.64	13.85	0.00	***
	Compressibility	0.18	3.72	0.00				
3	Transport capability	0.82	17.07	0.00	0.65	4.21	0.04	*
	Compressibility	0.18	3.80	0.00				
	Shearing resistance	-0.10	-2.05	0.04				
4	Transport capability	0.80	16.80	0.00	0.67	9.23	0.00	***
	Compressibility	0.16	3.40	0.00				
	Shearing resistance	-0.12	-2.62	0.01				
	OMMC	0.15	3.04	0.00				

a Dependent Variable: Overall comfort

Note: *:p<0.05; **: p<0.01; ***: p<0.001

The results of the hierarchical linear regression to predict subjective *overall comfort* perception are shown in Table 5-8. Pajamas fabric transport capability, compressibility, shearing resistance and OMMC were four strong predictors of subjective *overall comfort* perception. Transport capability, compressibility and OMMC have positive effects on subjective *overall comfort* perception, while fabric shearing resistance has a negative effect. Model 4 was selected to describe the relation between subjective *overall comfort* perception and pajamas fabrics' physical properties.

5.3.3 Effects of clothing on skin physiology

Hierarchical Linear Regression (HLR) has been performed to predict the relationship among factors and SCWC, TEWL, skin surface Sebum, surface acidity and overnight free urinary catecholamines.

SCWC

Table 5-6 shows the correlation matrix of the Pearson correlation and the significance of each variable. SCWC correlated with hydroscopicity of pajama and subjective perception of comfort significantly at $p \leq 0.05$ level or higher. SCWC did not correlate with environmental temperature, relative humidity and sleep quality in these two wear trials. Subjective perception of coldness and comfort was correlated with pajama hygroscopicity property ($p<0.05$); and sleep quality correlated with perception of coldness and comfort ($p<0.05$).

Table 5-9 Correlations between SCWC and other variables

	Correlations						
	Pearson Correlati	1	2	3	4	5	6
1	LnSCWC						
2	Hygroscopicity (hygroscopic=0)	-0.29**					
3	Overmfort	0.24*	0.11				
4	Sleep quality (goo	-0.02	0.04	-0.24			
5	Catecholamines (|	-0.11	-0.05	-0.10	0.01		
6	Coldness	0.15	-0.23*	0.34**	-0.17	-0.05	
7	Itchiness	0.12	-0.09	-0.07	0.01	0.19*	0.11

Note: *: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

Table 5-10 Model summary_LnSCWC

		Coefficients			**Model summary**			
Model		**Standardized Coefficients Beta**	**t**	**Sig.**	**R aquare**	**F change**	**Sig. F change**	
1	Hygroscopicity (hygroscopic=0)	-0.29	-2.57	0.01	0.08	6.62	0.01	***
2	Hygroscopicity (hygroscopic=0)	-0.32	-2.93	0.00	0.16	6.20	0.02	*
	Overmfort	0.27	2.49	0.02				
a	Dependent Variable: LnSCWC							

Note: *: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

The results of the HLR predicting change in LnSCWC are shown in Table 5-10. Fabric materials of pajamas (hygroscopicity) and subjective perception of overall comfort are two strong predictors of SCWC. Weak hygroscopic (polyester) pajamas have a negative effect on SCWC compared with hygroscopicity pajamas (reference variable--cotton). The perception of overall comfort has a positive effect on SCWC. Subjective perception of coldness, itchiness, stress index catecholamines and sleep quality are not significant predictors for SCWC. Model 2 is selected to describe the relation between SCWC, hygroscopic features of pajamas, and subjective perception of overall comfort.

TEWL

Table 5-11 shows the Pearson correlation matrix and the significance of each variable. TEWL correlated with subjective overall comfort sensation ($p<0.05$), pajama hygroscopicity ($p<0.01$), and fabric transport capability ($p<0.05$); TEWL did not correlate with fabric hydrophilic capacity, SCWC, fabric hydrophilicty and skin surface pH. Subjective overall comfort sensation correlated with SCWC and skin surface pH significantly ($p<0.05$); pajama hygroscopicity correlated with pajamas fabric transport capability and hydrophilic capacity significantly ($p<0.05$); pajamas fabric transport capability correlated with fabric hydrophilic capacity and hydrophilicity ($p<0.001$) significantly; pajamas fabric hydrophilic capacity correlated with SCWC significantly ($p<0.01$); and SCWC correlated with pajama fabric hydrophilicity significantly ($p<0.05$).

Table 5-11 Correlations between TEWL and other variables

	Correlations						
	Pearson Correlation	1	2	3	4	5	6
1	TEWL (g/hm^2)						
2	Hygroscopicity (hygroscopic=0)	-0.22*					
3	Overall comfort	0.19*	-0.12				
4	Transport capability	-0.21*	0.85***	0.14			
5	Hydrophilic capacity	-0.15*	0.62***	0.11	0.60***		
6	SCWC	0.15	-0.26**	0.24*	-0.25*	-0.32**	
7	pH	0.13	-0.09	-0.17	-0.01	-0.04	-0.06

Note: *: p<0.05, **: p<0.01, ***: p<0.001

Table 5-12 Model summary_TEWL

		Coefficients			Model summary			
Model		Standardized Coefficients Beta	t	Sig.	R aquare	F change	Sig. F change	
1	Overall comfort	0.23	2.22	0.03	0.05	4.92	0.03	*
2	Overall comfort	0.21	1.97	0.05	0.11	4.99	0.03	*
	Hygroscopicity (hygroscopic=0)	-0.23	-2.23	0.03				
a	Dependent Variable: TEWL							

Note: *: p<0.05, **: p<0.01, ***: p<0.001

The results of the HLR to predict change in TEWL are shown in Table 5-12. Subjective overall comfort sensation and fabric materials of pajamas (hygroscopicity) are two strong predictors of TEWL. Overall comfort sensation and weak hygroscopicity material (polyester) of pajamas both have a negative effect on TEWL. Pajamas fabric transport capability, fabric hydrophilic capacity, SCWC and skin surface pH were not significant predictors for TEWL. Model 2 was selected to describe the relationship between TEWL, subjective overall comfort and pajamas' hygroscopicity.

Sebum

Table 5-13 describes the correlation matrix of the Pearson correlation and the significance of each variable. Sebum correlated with pajama hygroscopicity (p<0.05), skin surface pH (p<0.01), over night free urinary catecholamines (p<0.01), sleep quality (p<0.001), and SCWC (p<0.05). Sebum did not correlate with environmental relative humidity, fabric differential wetting properties and fabric hydrophilic capacity. Pajamas fabrics' hygroscopicity property correlated with fabric differential wetting properties, fabric hydrophilic capacity and SCWC significantly (p<0.001).

Table 5-13 Correlations between sebum and other variables

	Correlations						
	Pearson Correlation	1	2	3	4	5	6
1	Sebum						
2	Hygroscopicity (hygroscopic=0)	0.20*					
3	pH	0.34**	-0.07				
4	Catecholamines (pmol)	0.30**	-0.02	0.15			
5	Sleep quality (good=0)	0.35***	0.16	0.02	0.05		
6	Relative humidity (%)	-0.17	0.05	0.07	-0.27	0.06	
9	SCWC	-0.23*	-0.26**	-0.13	-0.17	-0.12	-0.05

Note: *: p<0.05, **: p<0.01, ***: p<0.001

Table 5-14 Model summary_Sebum

		Coefficients			Model summary			
Model		Standardized Coefficients Beta	t	Sig.	R aquare	F change	Sig. F change	
1	Hygroscopicity (hygroscopic=0)	0.20	1.75	0.08	0.04	3.05	0.08	*
2	Hygroscopicity (hygroscopic=0)	0.23	2.17	0.03	0.23	5.76	0.02	*
	Catecholamines (pmol)	0.25	2.40	0.02				
3	Hygroscopicity (hygroscopic=0)	0.18	1.75	0.08	0.32	9.04	0.00	**
	Catecholamines (pmol)	0.24	2.39	0.02				
	Sleep quality (good=0)	0.30	3.01	0.00				

a Dependent Variable: Sebum

Note: *: p<0.05, **: p<0.01, ***: p<0.001

The results of the HLR to predict change in sebum are listed in Table 5-14. Subjective overall comfort sensation and fabric materials of pajamas (hygroscopicity) are two strong predictors of TEWL. Overall comfort sensation and weak hygroscopicity material (polyester) of pajamas both have a negative effect on TEWL. Pajamas fabric transport capability, fabric hydrophilic capacity, SCWC and skin surface pH were not significant predictors for TEWL. Model 2 was selected to describe the relationship between TEWL, subjective overall comfort and pajamas' hygroscopicity.

Skin surface pH

Table 5-15 presents the Pearson correlation matrix and their significance of each variable. Skin surface pH correlates with pajamas fabric transport capability (p<0.001), sebum (p<0.001), environmental average temperature (p<0.001) and overnight free urinary catecholamines (p<0.01). Skin surface pH does not correlate with sleep quality and fabric shearing resistance.

Table 5-15 Correlations between skin surface pH and other variables

Correlations							
	Pearson Correlation pH	1	2	3	4	5	6
1	Transport capability	-0.31***					
2	Sebum	0.39***	-0.24**				
3	Shearing resistance	0.12	0.21*	0.04			
4	Average temperature	-0.30***	0.80***	-0.39***	-0.01		
5	Catecholamines (pmol)	0.24**	-0.28**	0.41	0.14	-0.38***	
6	Sleep quality (good=0)	0.09	0.06	0.15*	0.03	0.02	-0.04

Note: *: p<0.05, **: p<0.01, ***: p<0.001

Table 5-16 Model summary_skin surface acidity (pH)

		Coefficients			Model summary			
Model		Standardized Coefficients Beta	t	Sig.	R aquare	F change	Sig. F change	
1	Transprot capability	-0.31	-3.43	0.00	0.10	11.76	0.00	***
2	Transport capability	-0.23	-2.64	0.01	0.20	14.27	0.00	***
	Sebum	0.33	3.78	0.00				

a Dependent Variable: pH

Note: *: p<0.05, **: p<0.01, ***: p<0.001

The results of the HLR predicting change in skin surface pH are shown in Table 5-16. Pajamas fabric transport capability and sebum are two strong predictors of skin surface acidity (pH). Pajamas fabric transport capability has a negative effect on skin surface pH and sebum has a positive effect on skin surface acidity (pH). Overnight free urinary catecholamines, and sleep quality are not significant predictors for skin surface acidity (pH). Model 2 is selected to describe the relation between skin surface pH, pajamas fabric transport capability and sebum.

5.3.4 Clothing-wearer interaction

Clothing-wearer interaction in stress (Over night free urinary catecholamines)

Correlation matrix of Pearson correlation and their significance of each variable is shown in Table 5-17. Overnight free urinary catecholamines correlate with pajamas fabric transport capability (p<0.001), fabric shearing resistance (p<0.05), and fabric compressibility (p<0.05). Overnight free urinary catecholamine does not correlate with sleep quality.

Table 5-17 Correlations between overnight free urinary catecholamines and other variables

Correlations				
Pearson Correlation	1	2	3	4
1 Catecholamines (pmol)				
2 Transport capability	-0.33***			
3 Shearing resistance	0.13*	0.12		
4 Compressibility	0.16*	-0.10	0.09	
5 Sleep quality (good=0)	-0.01	-0.08	0.03	0.04

Note: *: p<0.05, **: p<0.01, ***: p<0.001

Table 5-18 Model summary_Catecholamines

		Coefficients			Model summary			
Model		Standardized Coefficients Beta	t	Sig.	R aquare	F change	Sig. F change	
1	Transfer behavior	-0.33	-4.20	0.00	0.11	17.68	0.00	***
2	Transfer behavior	-0.35	-4.49	0.00	0.14	4.69	0.03	*
	Shearing resistance	0.17	2.17	0.03				
a	Dependent Variable: Catecholamines (pmol)							

Note: *: p<0.05, **: p<0.01, ***: p<0.001

Table 5-18 lists the results of the HLR predicting change in overnight free urinary catecholamine. Pajamas fabric transport capability and fabric shearing resistance are two strong predictors of overnight free urinary catecholamine. Pajamas fabric transport capability has a negative effect on overnight free urinary catecholamine; fabric shearing resistance has a positive effect on overnight free urinary catecholamine. Pajamas’ compressibility, sleep quality, and fabric elastic properties are not significant predictors for overnight free urinary catecholamines. Model 2 is selected to describe the relation between overnight free urinary catecholamine, pajamas fabric transport capability and shearing resistance.

Clothing-body interaction with sleeping quality

To investigate the relationship between subject’s sleep quality, comfort perception, and fabric physical properties, Binary Logistic Stepwise Forward Logistic Regression was applied to perform the analysis. The factors that influenced sleep quality were explored by logistic regression. Good sleep quality is coded with 'SQ', the reference category '0' = 'good sleep quality', and 'PSQ', the 'poor sleep quality' category is coded '1'.

The classification table indicates the model could predict 89.36% of the overall data (Table 5-19). There is no missing data issue.

Table 5-19 Classification of data

Classification Table(a,b)					
Observed			Predicted		
			Sleep quality		Percentage Correct
			Good sleep quality	Poor sleep quality	Good sleep quality
Step 0	Sleep quality	Good sleep quality	84	0	100
		Poor sleep quality	10	0	0
	Overall Percentage				89.36

a Constant is included in the model.
b The cut value is .500

Table 5-20 Model summary_sleep quality

Model Summary			
Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	59.68	0.04	0.09

a Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

The model summary indicates that there is one model generated from the analysis (Table 5-20).

Table 5-21 Variables in the equation_sleep quality

Variables in the Equation							
		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1(a)	Overall comfort	-0.32	0.15	4.36	1	0.04	0.73
	Constant	0.33	1.16	0.08	1	0.78	1.39

a Variable(s) entered on step 1: Overall comfort.

From the table of Variables in the equation, the model can be explained as the 'score of sleep quality' in which expected a 0.32 decrease in the log-odds of subjective overall comfort perception, holding all other independent variables constant. In this model, subjective overall comfort perception (OC) is significant (less than 0.1).

The regression equation could be express as:

$$P_{sq} = \frac{1}{1+e^{-(-0.33-0.32*OC)}} = 0.97 \quad (5\text{-}1)$$

$$P_{psq} = 1 - P_{sq} = 0.03 \quad (5\text{-}2)$$

$$Oddsratio = \frac{P_{sq}}{P_{psq}} = 32.33 \quad (5\text{-}3)$$

The logistic regression results imply that subjective overall comfort perception of the fabrics of pajamas has significant positive effect on good sleep quality.

5.4 Discussion and conclusions

A framework was established based on the HLR, which is summarized in Table 5-22 and Fig. 5-1, describing interactions of fabric thermal/mechanical properties, neuropsychological responses and skin physiology.

Table 5-22 Effects of clothing on skin physiology under mildly cold condition

Factors	SCWC	TEWL	Sebum	Skin surface acidity	Over night free urine catecholamines	Coldness	Overall comfort	Sleep quality
Weak hygroscopicity (hygroscopic=0)	-	-	+			-		
Hydrophobicity (hydrophilic=0)						-		
Pajamas fabric transport capability				-	-		+	
Pajamas fabric shearing resistance				+	+		-	
Pajama compressibility							+	
OMMC							+	
TEWL								
Skin surface pH			+					
Sebum				+				
Sleep quality (good=0)			+					
Over night free urine catecholamines			+					
Subjective overall comfort	+	+						+

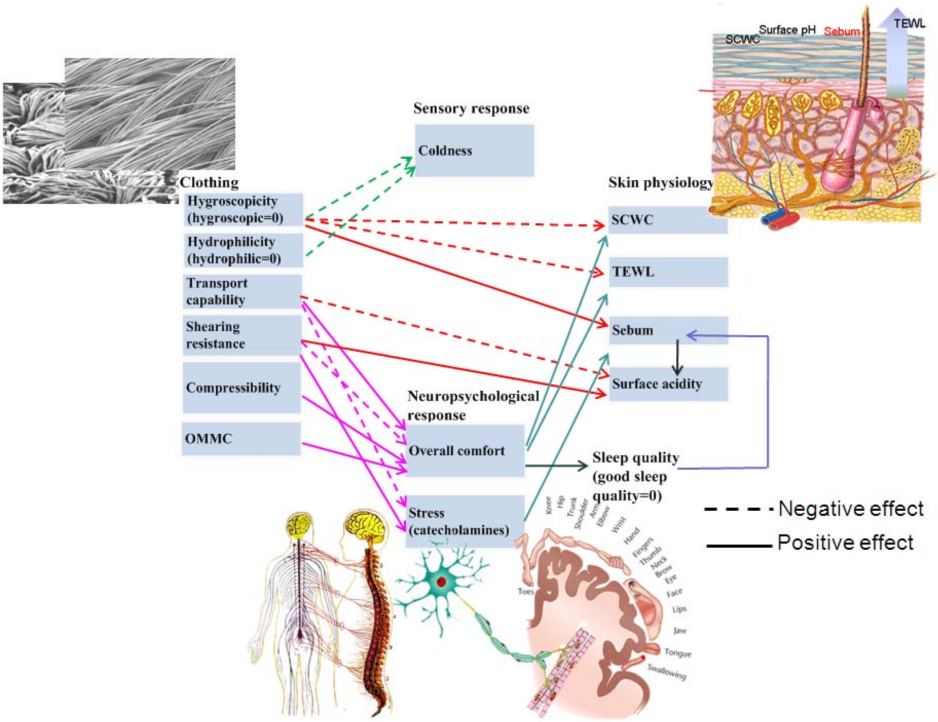


Figure 5-1 Clothing-wearer interactions in sensory response, skin physiological and neuropsychological response in mildly cold condition

From the illustration in Fig. 5-1, it is seen that fabric plays various roles on skin physiology, sensation, and psychology within a network in mildly cold condition. Properties of fabric influence skin physiology, sensory response and psychological response of human body. Psychological status of our body impact on skin physiology as well.

Hygroscopic fabric of clothing enhances SCWC and TEWL, and reduces sebum when compared with weak hygroscopic fabric. Its potential mechanisms have been interpreted in Chapter 3 and 4. Fabric transport capability (water vapor permeability, thermal conductivity, ands air permeability) has a negative effect on skin surface acidity, while fabric shearing resistance has a positive effect. The transport capability of fabric largely affects heat release of human body to environment probably due to its capability of heat releasing from microclimate to extra environment. Fabric with poor transport capability inhibits heat release from human body, making accumulation of heat in the surrounding environment of the skin, and thus increasing skin surface acidity (Mauro 2006; Choi et al. 2007).

Fabric transport capability, shearing resistance, compressibility and OMMC significantly affect psychological status of human body in terms of overall comfort and stress level. Fabric with higher transport capability enhances heat release, reduces heat accumulation surrounding the skin, improves overall comfort sensation, and reduces stress level in mildly cold condition. Fabric with higher shearing and surface roughness significantly incorporates stiffness and roughness thus reducing overall comfort sensation score and increasing stress level. Fabric with better compressibility and moisture management capacity implies that the fabric is soft and keeps the skin dry, improving overall comfort sensation.

Given the importance of the psychological status of the human body, overall comfort sensation has significant positive effect on SCWC and TEWL, which may due to the fact that comfort sensation induces vasodilatation of the skin vessels, increases SCWC and TWEL.

It also has been noted that higher stress level increases sebum and overall comfort sensation positively impacting on sleep quality.

Weak hygroscopicity and hydrophobic properties have a negative effect on coldness sensation which suggests that one would feel colder wearing weak hygroscopic fabric compared with hygroscopic fabric; and feel warmer wearing hydrophilic fabric compared with hydrophobic fabric. Positive effects from poor sleep quality on sebum also has been noted.

This analysis confirms that fabrics influence skin physiology through their hygroscopic properties and transport capability under mildly cold condition. Physiological effects from overall comfort sensation, sleep quality and stress also influence skin physiology in terms of skin surface pH, and sebum as found in this study. The relationships among fabric, skin physiology and psychology have been thus elucidated.

Chapter 6 Effects of Fabric on Skin Physiology in Hot Environment

6.1 Introduction

In previous chapters (see 3, 4 and 5), effects of fabric on skin physiology in mildly cold condition have been systematically investigated. The study results indicated that hygroscopic property of fabric play important roles in stratum corneum hydration and thermal sensory response. Other fabric properties, such as transport capability, shearing resistance, and compressibility play roles on both skin physiology and sympathetic nervous system activity. These results provide a map of effects of clothing on skin physiology in our normal daily life, when sweating is absent.

Based on understanding of human physiological response in hot environment with activity (running), convection and evaporation of sweat carries the heat away from the surface of the body to the environment to reduce heat stress of the human body. Both evaporation and conduction process could be influenced by such transport capability of fabric.

To fulfill the fifth objects of this study, in this chapter, attempts are made to verify hypotheses *III* and *IV* (proposed in Chapter 2) have been verified by wear trial.

Hypothesis III

Clothing may influence thermal physiology of human body in terms of core temperature and skin temperature in hot weather as it affects the evaporation and conduction heat loss of human body.

Hypothesis IV

Clothing could influence water content of stratum corneum and skin evaporation in hot environment by influencing heat and moisture and liquid water transfer between human body and environment.

A wear trial has been conducted to study effects of fabrics, cotton and polyester, with hydrophilic and hydrophobic surface treatment, on skin physiology and thermal physiology during resting, running and recovering in hot condition and will be reported in this chapter.

6.2 Methods

A cross-over, blinded designed wear trial was carried out to investigate influence of fabric, polyester and cotton, and with hydrophilic and hydrophobic surface treatment, on skin physiology and thermal physiology in hot environment under different activities. Ten male and ten female athletes were selected as subjects to participate in the study. The menstrual cycle phase in the female subjects was checked and they served as subjects when they were in the follicular phase.

The experimental protocol was approved by the Hong Kong Polytechnic University Human subjects ethics sub-committee.

The twenty participants were aged between 19 and 22 years, with an average height of 170.85±8.23 cm, and an average body mass of 57.65±9.87 kg. They were asked to maintain a regular life style from one week before and the whole experimental period. They were prohibited from smoking, drinking alcohol, and performing heavy exercise during the experimental period. Participants were also prohibited from using body cream and/or glycerin on the body surface, except their faces, hands and feet.

Subjects were invited to have a pre-test before the formal experiment to predict their maximal aerobic power from their maximum heart rate using a Polar Heart Rate Monitor (810i^{TM}). During each experiment, each subject was required to enter the chamber, fixed sensor, changed clothing (randomly selected), then, rested for 30 minutes to reach equilibrium. The test conditions had been set at temperature 32±0.5°C, relative humidity 50±5% with air velocity varying around 0.50m/s. At the end of equilibrium period, the subjects were asked to run on a treadmill for 20 minutes at their 70% maximum heart rate (HRmax). This condition allowed the subjects to produce sweating. Further recovering for 30 minutes was required to obtain skin and thermal physiological response.

During the experiment, to examine the effects of clothing on human physiological response, heat rate, skin temperature, and ear canal temperature were recorded continually during the experiment. Skin conductance response (SCR) was used to inspect the sweating loading time during wearing garments made from different fabrics. Skin physiological parameters, SCWC and skin water evaporation were measured at time points of 20 and 50 minutes. To understand the physical effect of fabric, clothing microclimate temperature and humidity were recorded continually during the experiment; and, clothing surface temperature was tested by infra thermograph at 30, 50, and 80 minutes.

6.2.1 Materials

Four sets of experimental garments (cotton and polyester with hydrophilic and hydrophobic treatment) with long sleeves and long pants were used in wear trial. The style of the garments has been described in Chapter 2 (Fig 2-2). The garments were made from 32s following the same structure of knitting for the four types of fabrics i.e., for hydrophilic polyester, hydrophobic cotton, hydrophobic polyester, and hydrophilic cotton.

6.2.2 Measurement

Fabric physical properties have been measured following methods described in Chapter 5. Details of the results are listed in Appendix III.

Heat rate was recorded by Polar Heart Rate Receiver (810i^{TM}) (Polar Electro, U.S.A). Ear canal temperature was measured continuously by a temperature sensor "LT-ST 08-00" (Gram, Japan, accuracy 0.1°C). Body skin temperature was measured by LT-ST 08 (Nikkiso-Therm, Japan) every 30 second for 50 minutes at four different sites: chest, upper arm, thigh, and calf. The calculation for the mean skin temperature (T_{sk}) was determined by Ramanathan's formula, $T_{sk}=0.3T_{chest}+0.3T_{bicep}+0.2T_{thigh}+0.2T_{calf.}$ (Ramanathan 1964). Clothing-skin microclimate relative humidity was measured by humidity sensors (HIH-3610, Honeywell, USA) with a data acquisition system (PCL818H with two extended amplifier and multiplexer boards PCLD 789D, from ADVANTECH®). Microclimate absolute humidity was calculated from:

$$P_{sa} = \exp(18.956 - \frac{4030.18}{t + 235}) \quad (6\text{-}1)$$

$$P_a = RH \; P_{sa} \quad (6\text{-}2)$$

$$AH = 2.17 \frac{P_a}{T} \quad (6\text{-}3)$$

Where:

RH is relative humidity (%)

P_a is of partial vapour pressure in kP_a,

P_{sa} is water vapour pressure, at temperature t °C,

AH is absolute humidity in Kg/m^3

Clothing surface temperature was measured by infrared thermograph with Thermal Image Analyzer (Nikon Thermal Vision LAIRD-S270, Nikon, Japan). Stratum corneum water content and skin water evaporation were measured by Corneometer CM825 and Tewameter TM300 (CK, German) in the region of the central back area of the spinal column from T4 to T6. Skin conductance response was measured using large lead electrodes lined with porous material in the region of infrasternal notch. The voltage curve was recorded, and the point of voltage decreased indicated that sweating had occurred.

6.2.3 Statistic

In this study, the fabric properties were classified into a few factors by factor analysis to reduce the number of variables, including thermal properties, liquid water transport properties and mechanical properties. SPSS Data Reduction function was applied to check and confirm the classification.

Repeated Measure-ANOVA (Clothing × time) was used to evaluate whether fabrics (material and treatment) influence skin hydration and body physiology. These ANOVAs compared within-subject skin hydration and body physiology wearing four sets of clothing. The basic assumptions underlying this test were also examined (i.e., normality and homogeneity of variance). Where significant interaction effects were found, post-hoc analysis was performed using a Tukey's HSD test for pairwise comparisons. Data were considered statistically significant at $p<0.05$, using

Sphericity Assumed or Greenhouse-Geisser corrections based on Mauchly's Test of Sphericity. Variables with a univariate significance level of $p<0.05$ were included in the model.

Hierarchical Linear Regression (HLR) was performed to analyze the relationship among fabric material, activity, skin physiology and human body thermal physiology to explore the mechanism of influence of fabric on skin physiology. The influence of fabric materials and ‘Time (activity)’ was studied as categorical variables. Fabric material in terms of ‘hydrophilic’ and ‘hygroscopic’ was regarded as reference category. A 2-tailed p value of $p<0.05$ was considered to be significant.

6.3 Results

Skin and human physiological data obtained from the study are summarized in Table 6-1. Detailed analysis will be presented in the following sections.

Table 6-1 Outcome of variables (Mean±STD)

Garmant	Time	Skin evaporation (g/m^2/h)	SC water content (%)	Clothing surface temperature (° C)	Skin temperature (° C)
Hydrophilic Polyester	Resting	28.22±12.76	90.43±18.07	31.96±0.42	34.83±1.10
	Running			31.46±0.46	33.49±1.34
	Recovering	35.19±8.32	102.83±13.34	31.59±0.57	33.19±1.51
Hydrophobic cotton	Resting	24.63±15.00	76.52±21.73	32.03±0.46	34.76±0.82
	Running			31.66±0.57	34.26±1.00
	Recovering	31.14±9.42	104.87±9.07	31.85±0.58	33.49±1.08
Hydrophobic Polyester	Resting	26.31±16.00	92.70±16.85	32.07±0.39	34.90±0.89
	Running			31.63±0.40	33.57±0.70
	Recovering	36.05±14.68	102.37±8.42	31.41±0.48	33.54±0.91
Hydrophilic cotton	Resting	22.67±12.79	81.76±16.83	32.06±0.58	35.09±0.71
	Running			31.47±0.62	34.48±0.82
	Recovering	27.70±8.64	100.90±9.74	31.47±0.61	34.12±0.97

Garmant	Time	Ear cannal temperature (° C)	Microclimate humidity (Kg/m^3)	Heart rate
Hydrophilic Polyester	Resting	35.61±0.31	33.12±6.05	90.87±14.34
	Running	35.79±0.25	39.76±7.85	128.30±19.52
	Recovering	35.78±0.27	40.52±6.58	98.31±12.82
Hydrophobic cotton	Resting	35.56±0.36	33.45±9.48	85.33±11.04
	Running	35.76±0.24	40.82±6.95	130.07±15.03
	Recovering	35.69±0.29	40.02±6.79	91.96±21.24
Hydrophobic Polyester	Resting	35.56±0.25	31.73±5.48	85.39±11.27
	Running	35.73±0.34	37.40±4.69	123.65±15.58
	Recovering	35.66±0.26	41.42±5.98	93.75±10.31
Hydrophilic cotton	Resting	35.81±0.19	34.65±10.01	85.33±14.89
	Running	35.95±0.22	45.13±3.32	130.88±19.79
	Recovering	35.89±0.33	46.57±5.47	98.18±12.83

6.3.1 Skin conductance response

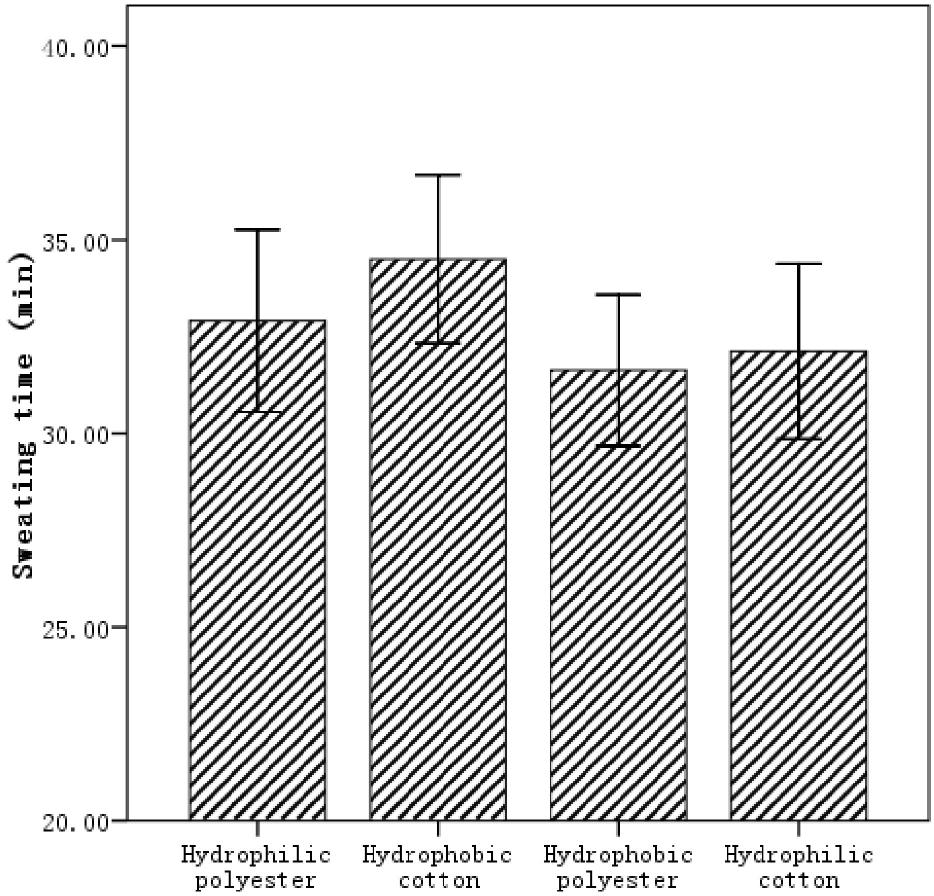


Figure 6-1 Skin conductance response

In this trial, sweating occurred in all cases. Skin conductance response time for hydrophobic cotton group seems later than other groups, indicating that sweating time was delayed when wearing hydrophobic cotton than others (Fig 6-1). However, it is not statistically significant (F=1.78, p=0.162).

This results indicated that all subjects, no matter whether wearing cotton or polyester with hydrophilic or hydrophobic treatment, were sweating during running at 70%HRmax.

6.3.2 Skin water evaporation

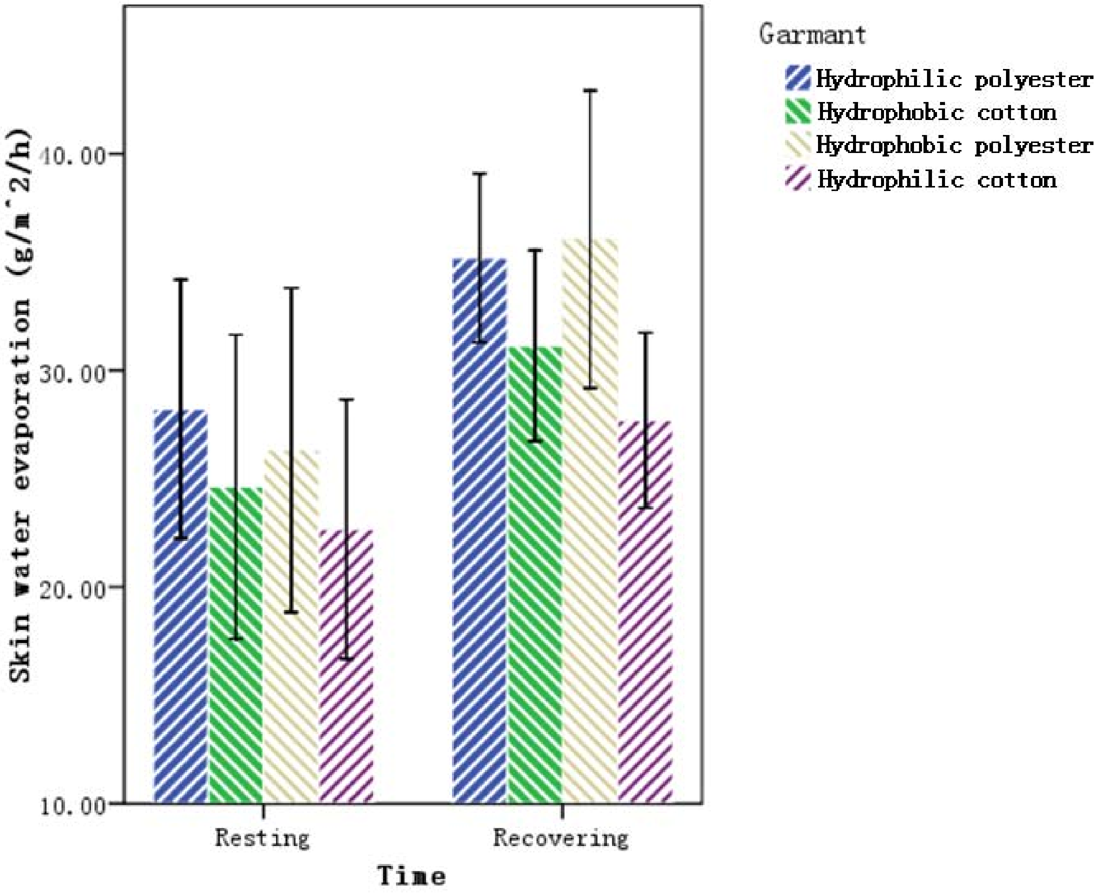


Figure 6-2 Skin water evaporation

Applying Repeated Measurement, effects of clothing on skin water evaporation is obtained from the following statistical results (Table 6-2 and 6-3):

Table 6-2 Mauchly's test of sphericlty

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

Within Subjects Effe	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
factor1	.791	4.162	5	.527	.864	1.000	.333
factor2	1.000	.000	0	.	1.000	1.000	1.000
factor1 * factor2	.861	2.658	5	.753	.907	1.000	.333

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed depen(proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected displayed in the Tests of Within-Subjects Effects table.

b.

Design: Intercept
Within Subjects Design: factor1+factor2+factor1*factor2

Table 6-3 Tests of within-subjects effects

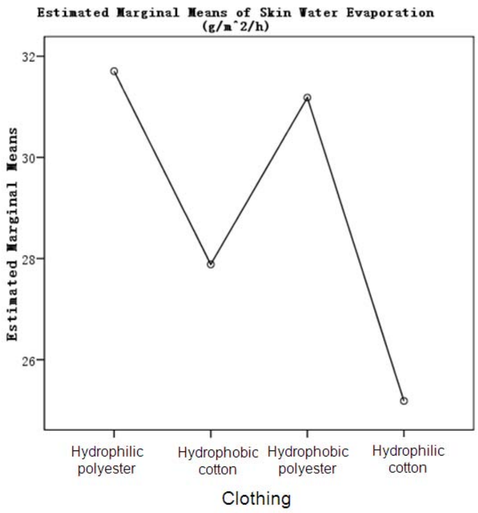
Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
factor1	Sphericity Assumed	1115.728	3	371.909	2.242	.093
	Greenhouse-Geisser	1115.728	2.593	430.252	2.242	.103
	Huynh-Feldt	1115.728	3.000	371.909	2.242	.093
	Lower-bound	1115.728	1.000	1115.728	2.242	.151
Error(factor1)	Sphericity Assumed	9455.186	57	165.880		
	Greenhouse-Geisser	9455.186	49.271	191.903		
	Huynh-Feldt	9455.186	57.000	165.880		
	Lower-bound	9455.186	19.000	497.641		
factor2	Sphericity Assumed	1995.980	1	1995.980	5.916	.025
	Greenhouse-Geisser	1995.980	1.000	1995.980	5.916	.025
	Huynh-Feldt	1995.980	1.000	1995.980	5.916	.025
	Lower-bound	1995.980	1.000	1995.980	5.916	.025
Error(factor2)	Sphericity Assumed	6410.141	19	337.376		
	Greenhouse-Geisser	6410.141	19.000	337.376		
	Huynh-Feldt	6410.141	19.000	337.376		
	Lower-bound	6410.141	19.000	337.376		
factor1 * factor2	Sphericity Assumed	116.058	3	38.686	.437	.728
	Greenhouse-Geisser	116.058	2.720	42.673	.437	.709
	Huynh-Feldt	116.058	3.000	38.686	.437	.728
	Lower-bound	116.058	1.000	116.058	.437	.517
Error(factor1*factor2)	Sphericity Assumed	5048.745	57	88.574		
	Greenhouse-Geisser	5048.745	51.675	97.702		
	Huynh-Feldt	5048.745	57.000	88.574		
	Lower-bound	5048.745	19.000	265.723		

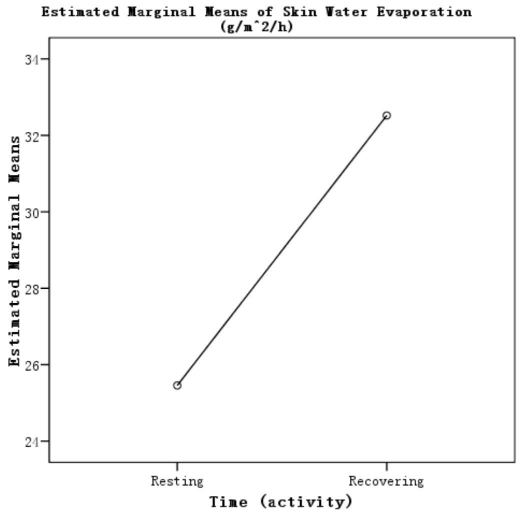
Summarizing the statistical results, Table 6-4 lists the effects of clothing on skin water evaporation. Same method is applied in the analysis of other parameters.

Table 6-4 Effects of clothing on skin water evaporation

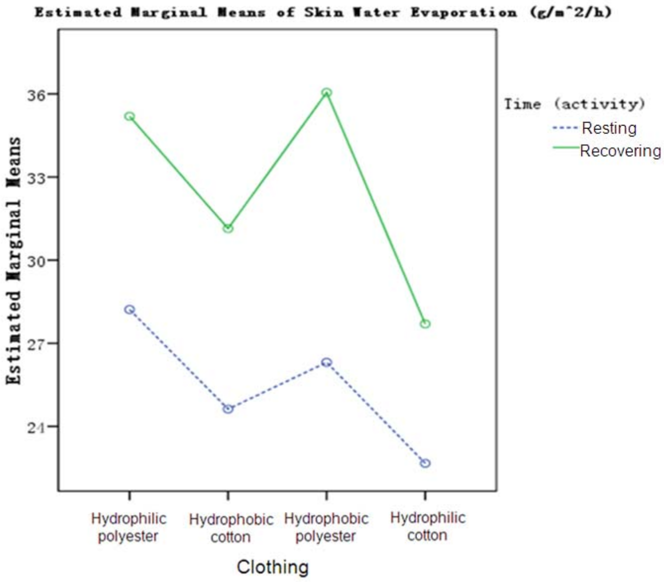
Tests of Within-Subjects Effects						
Effects		**Type III Sum of Squares**	**df**	**F**	**Sig.**	
Clothing	Greenhous-Geisser	1115.728	2.59	2.242	0.103	
Time (activity)	Huynh-Feldt	1995.980	1.00	5.916	0.025	*
Clothing * Time(Activity)	Greenhous-Geisser	116.058	2.72	0.437	0.709	



(a)



(b)



(c)

Figure 6-3 Estimated marginal means of skin water evaporation wearing different clothing (a), in different time (activity) (b), and wearing different clothing during different activity (c)

Skin water evaporation was measured during resting and time stopping running to obtain influence of fabric material and treatment on skin physiology in hot condition (Fig. 6-2). Clothing tends to influence skin water evaporation during recovering ($F=2.24$, $p=0.093$); Time (activity) has significant effects on skin water evaporation ($F=5.92$, $p<0.05$); and Clothing by Time (activity) has no interaction on skin water evaporation (Table 6-4).

Skin water evaporation in polyester groups is higher than in cotton groups (Fig. 6-3 (a). This pattern was present both during resting and recovering due to its lower air resistance property (Fig. 6-3 (c)). Skin water evaporation during recovering is higher than resting (Fig. 6-3 (b)).

Post Hoc analysis indicated that skin water evaporation in hydrophilic polyester group ($p<0.05$) is significantly higher than in hydrophilic cotton; hydrophobic polyester groups tends to be higher than in hydrophilic cotton ($p=0.051$).

These results show that skin water evaporation increased to release heat from body to environment due to the increase in metabolic rate. It also indicates that in hot climate wearing polyester clothing promoted skin water evaporation which perhaps stemmed from its transport capability.

6.3.3 SCWC

Table 6-5 Effects of Clothing and Time (activity) on SCWC

Tests of Within-Subjects Effects						
Effects		**Type III Sum of Squares**	**df**	**F**	**Sig.**	
Clothing	Sphericity Assumed	1499.102	3	2.810	0.047	*
Time (activity)	Sphericity Assumed	12101.929	1	40.044	0.000	***
Clothing * Time(Activity)	Sphericity Assumed	2076.690	3	4.075	0.011	*

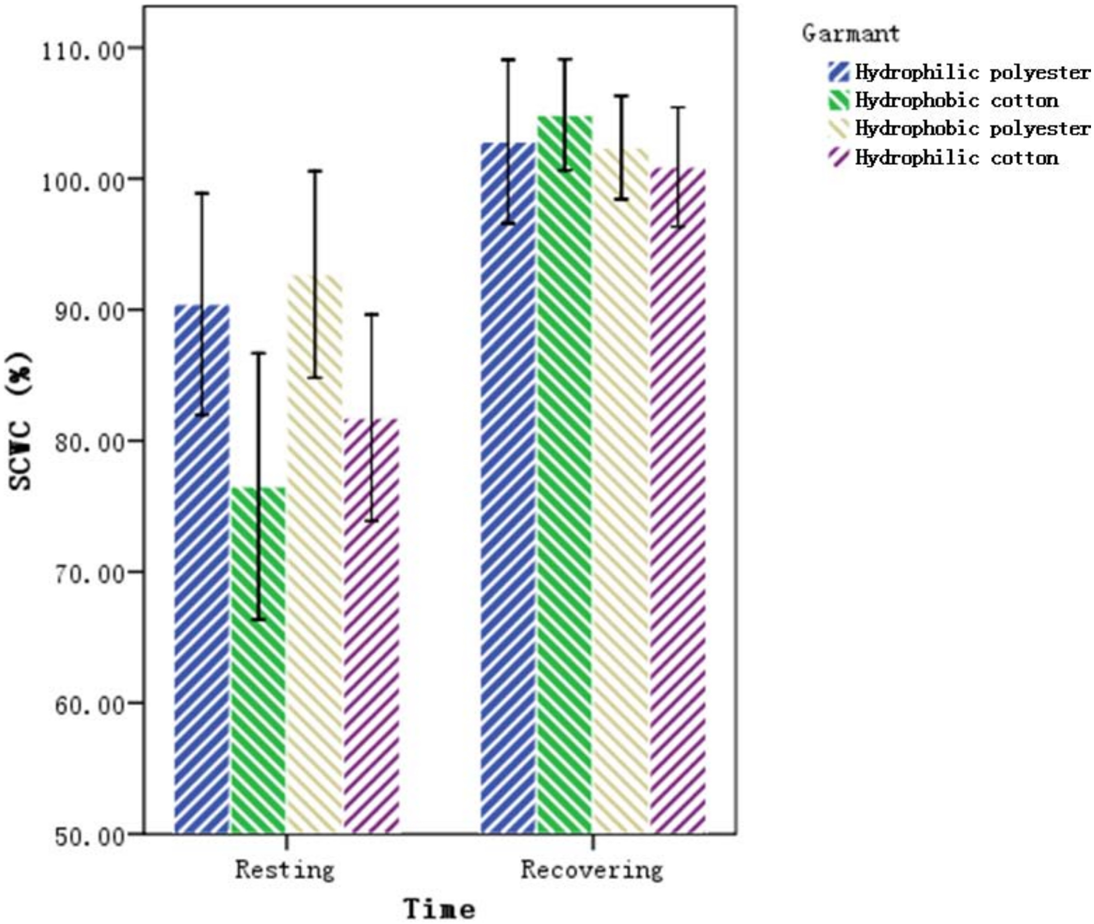


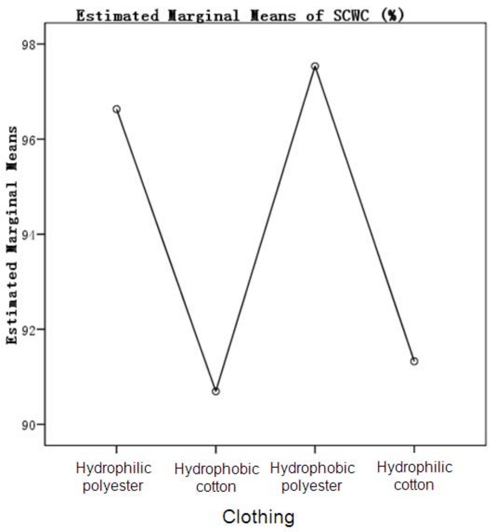
Figure 6-4 SCWC during resting and recovering

SCWC was measured during resting and at the time point of stopping running to study the effects of fabric on skin physiology, which is provided in Figure 6-4. In hot environment (32°C, 50%), fabric has significant effects on SCWC ($F=2.81$, $p<0.05$) (Table 6-5). Time (activity) also has significant effects on SCWC ($F=40.04$, $p<0.000$). Further, a significant Clothing by Time (activity) interaction effect ($F=4.08$, $p<0.05$) was noted.

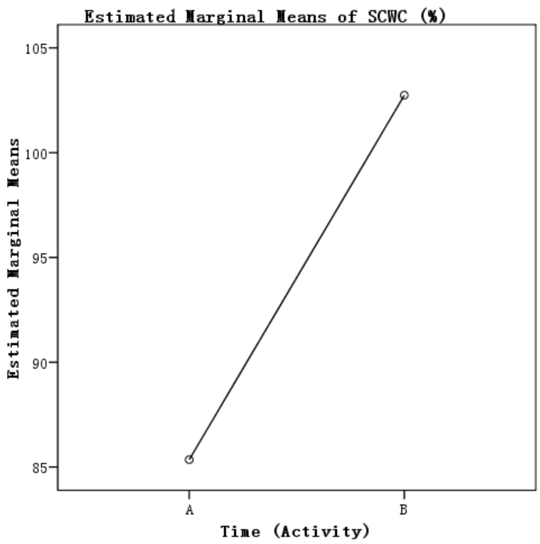
Post Hoc analysis shows that SCWC in hydrophilic polyester group tends to be higher than in hydrophobic cotton group ($p=0.094$). And it is higher in hydrophobic polyester group than that in hydrophobic cotton group ($p<0.05$).

SCWC is higher in polyester groups than in cotton groups during resting (Fig 6-5 (a) (c)). This implies that higher skin moisutrization occurs in polyester groups than cotton groups, which might be because of stronger water evaporation from inside of body to outside in polyester groups during resting in hot climate.

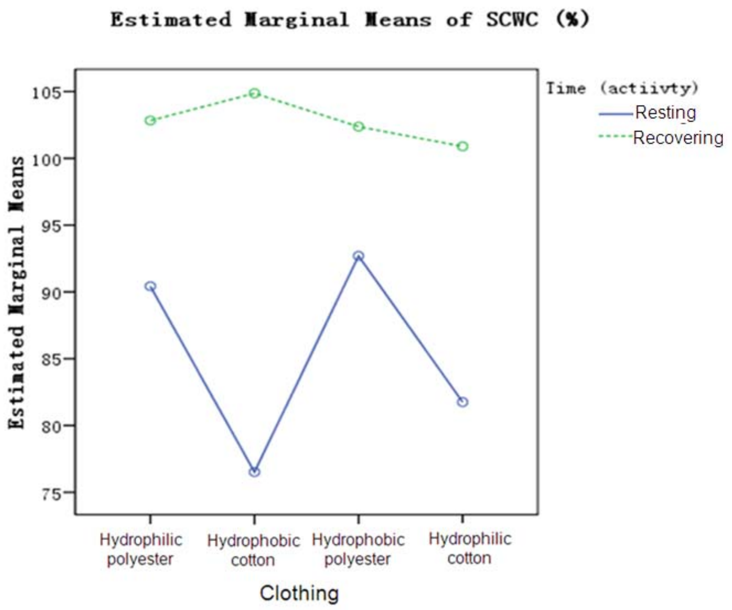
After running, when sweating occurred, SCWC reaches nearly 100% (Fig. 6-5 (b)) in all four groups, which confirms that stratum corneum swelled as it absorbed moisture/sweat water in hot environment during running.



(a)



(b)



(c)

Figure 6-5 Estimated marginal means of SCWC wearing different clothing (a), in different time (activity) (b), and wearing clothing during different activities (c)

6.3.4 Heart rate

Table 6-6 Effects of Clothing and Time (activity) on heart rate

Tests of Within-Subjects Effects						
Effects		Type III Sum of Squares	df	F	Sig.	
Clothing	Sphericity Assumed	888.533	3	1.638	0.191	
Time (activity)	Greenhouse-Geisser	76459.999	1.480	182.460	0.000	***
Clothing * Time(Activity)	Greenhouse-Geisser	811.248	3.241	1.089	0.363	

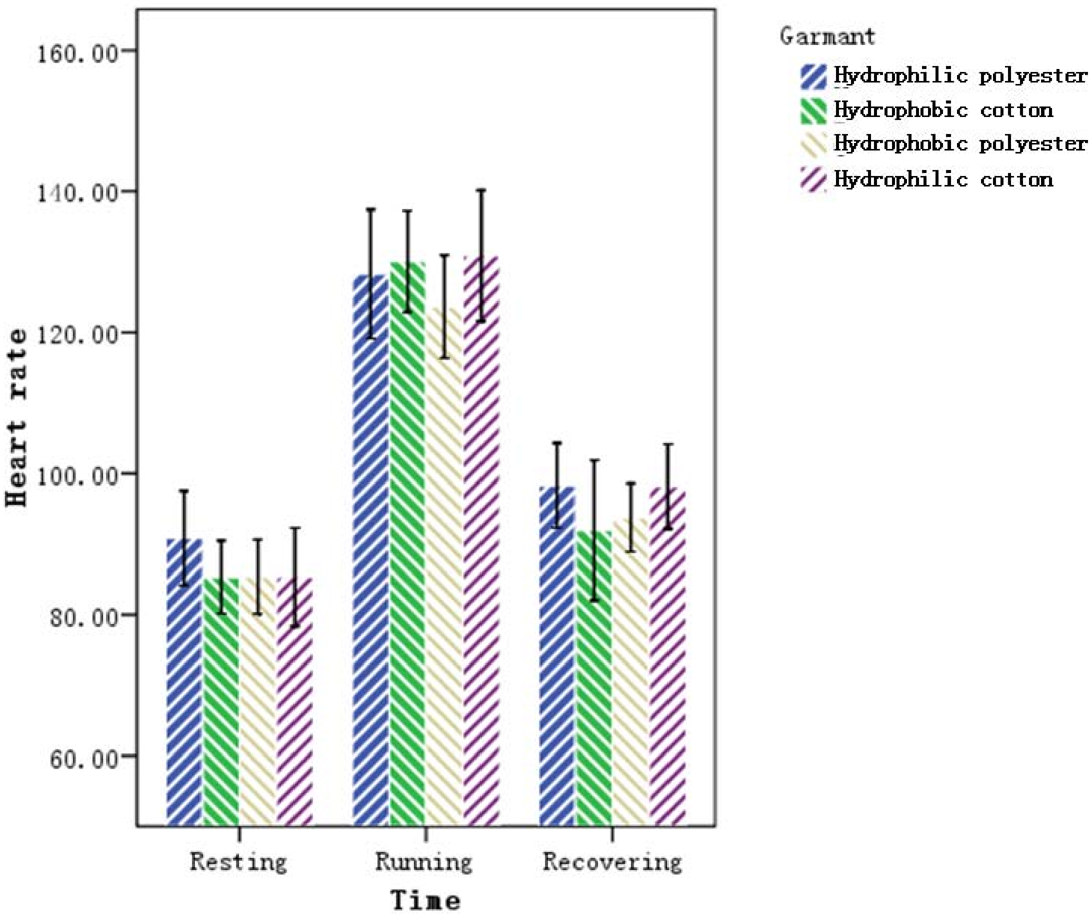
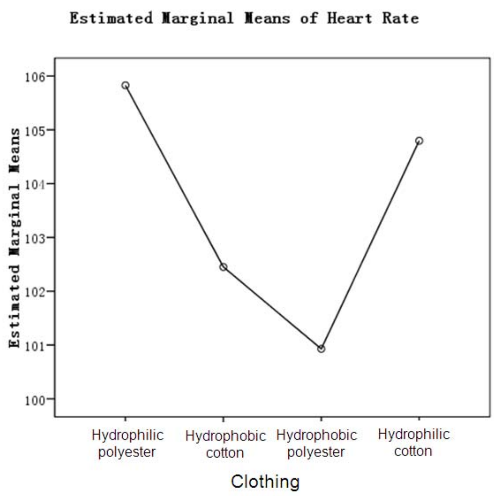
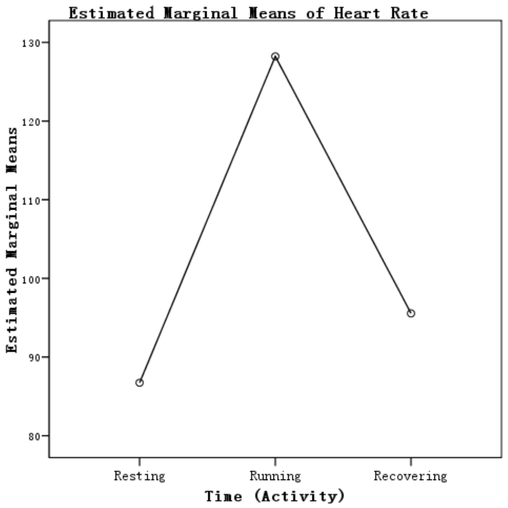


Figure 6-6 Heart rate during resting, running and recovering

Clothing has no significant effect on heart rate in the wear trial (F=1.638, p=0.191), while Time (activity) has significant effect (F=182.460, p<0.000). There is not Clothing by Time (activity) interaction effects on heart rate (F=1.089, p=0.363) (Table 6-6). Higher heart rate (p<0.05) was found in hydrophilic polyester group during resting. During running and recovering, the heat rate was mainly influenced by work load (Smolander et al. 1991).



(a)



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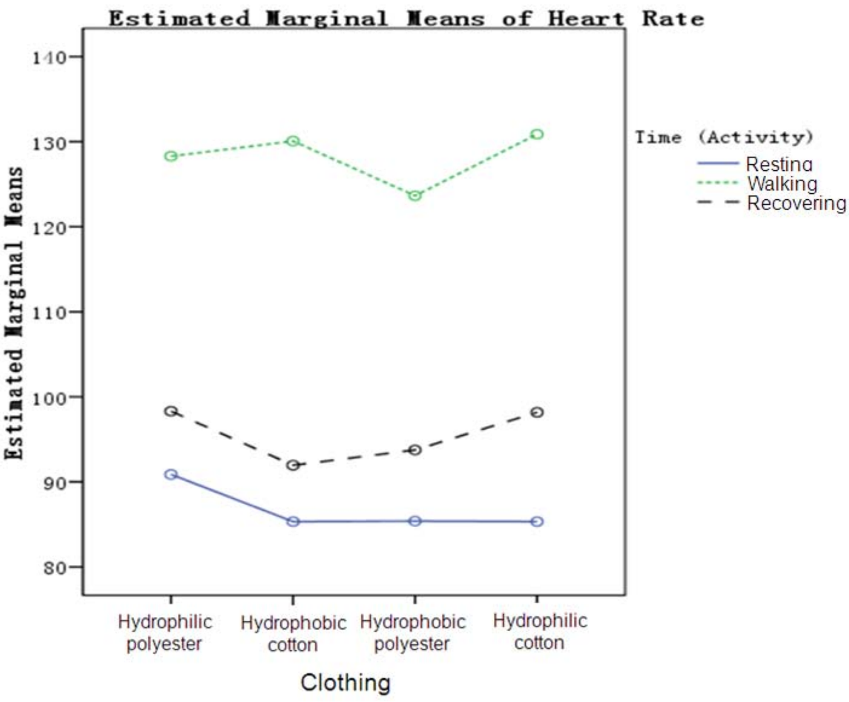


(c)

Figure 6-7 Estimated marginal means of heart rate wearing different clothing (a), in different time (activity) (b), and wearing clothing during different activity (c)

Heart rate during running is significantly higher than in resting and recovering in all four groups (Fig. 6-7 (b) and (c)).

6.3.5 Slope of heart rate change

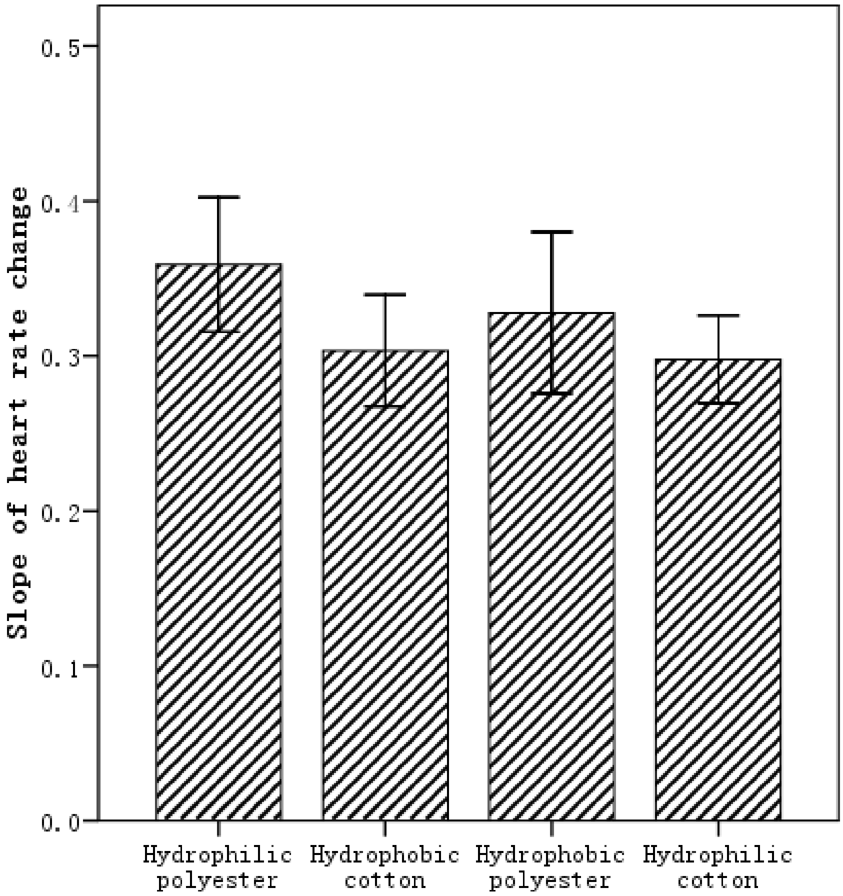


Figure 6-8 Heart rate change

The change of heart rate was defined as slope of heart rate increase from start of running till the flat line of heart rate was archived. (Running at the speed which was adjusted to archive their speed at 70%HRmax within 10 second), This implied that the autonomic nervous system was activated (Falcone et al. 2005). Change of heart rate tends to be influenced by Clothing (F=2.71, p=0.053).

Change of heart rate in polyester groups is higher than that in cotton groups. It suggested that heart rate increased faster than in cotton groups, implying that heart rate adjustment in polyester groups tends to be faster than in cotton groups (Fig. 6-8).

The results show that autonomic nervous system might get activated more quickly when wearing polyester rather than cotton during start of running.

6.3.6 Ear canal temperature

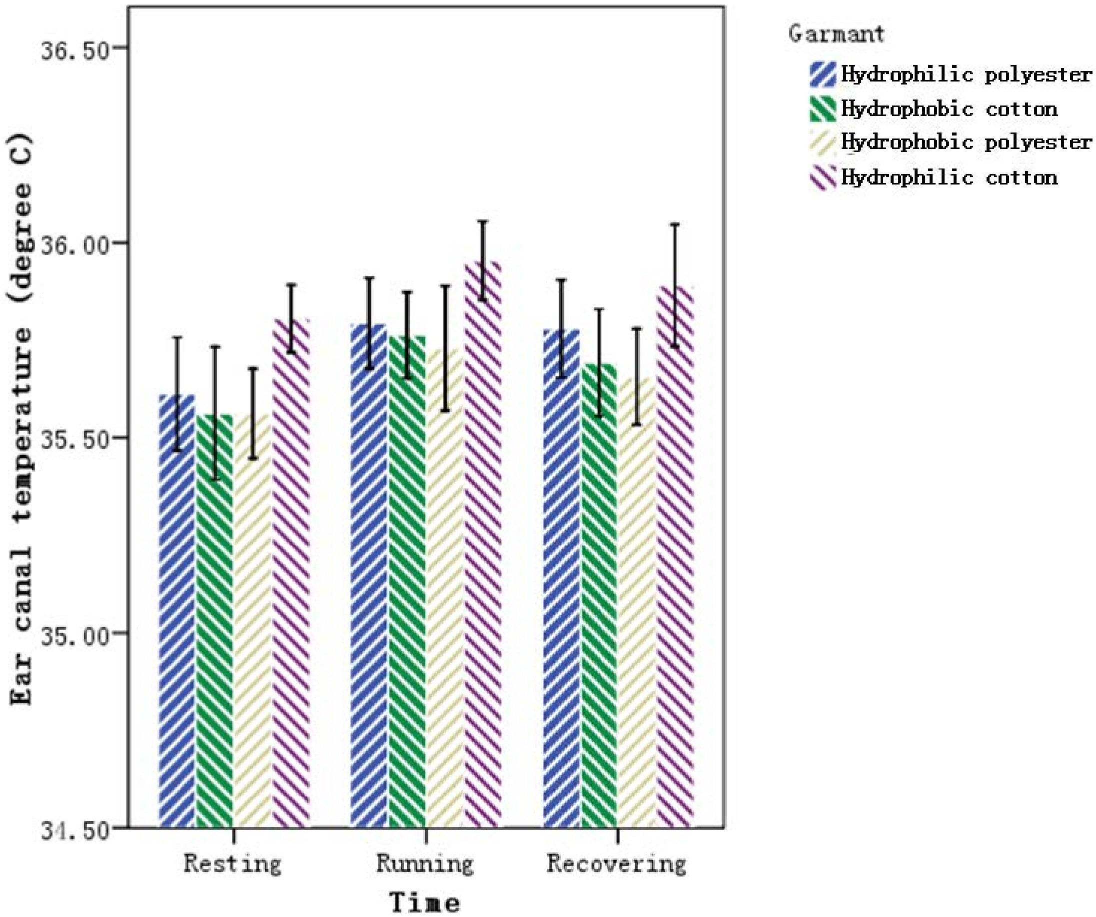
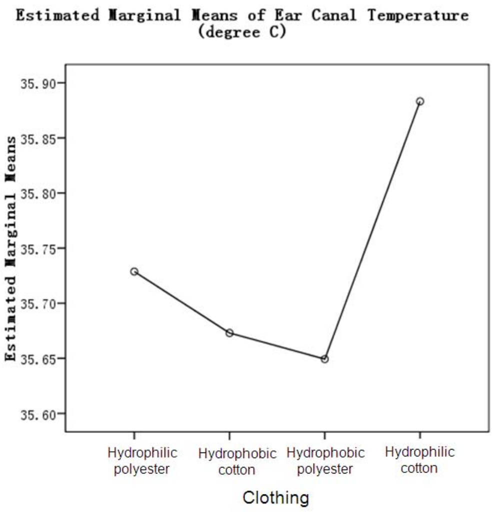


Figure 6-9 Ear canal temperature

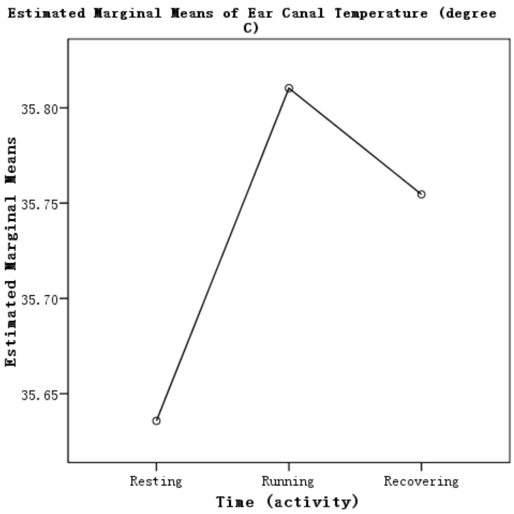
Table 6-7 Effects of Clothing and Time (activity) on ear canal temperature

Tests of Within-Subjects Effects						
Effects		**Type III Sum of Squares**	**df**	**F**	**Sig.**	
Clothing	Sphericity Assumed	1.991	3	6.087	0.001	**
Time (activity)	Sphericity Assumed	1.272	2	14.914	0.000	***
Clothing * Time(Activity)	Greenhouse-Geisser	0.054	3.760	0.265	0.890	

Ear canal temperature, as an important index of heat stress, shows the human physiological response in hot environment when running. Ear canal temperature when wearing four kinds of clothing during different activities is illustrated in Fig 6-9. Statistical analysis results show that Clothing has significant effect on ear canal temperature (F=6.087, $p<0.01$), and Time (activity) also has significant effect (F=14.914, $p<0.001$). But no Clothing by Time (activity) interaction effects has been found (Table 6-7).



(a)



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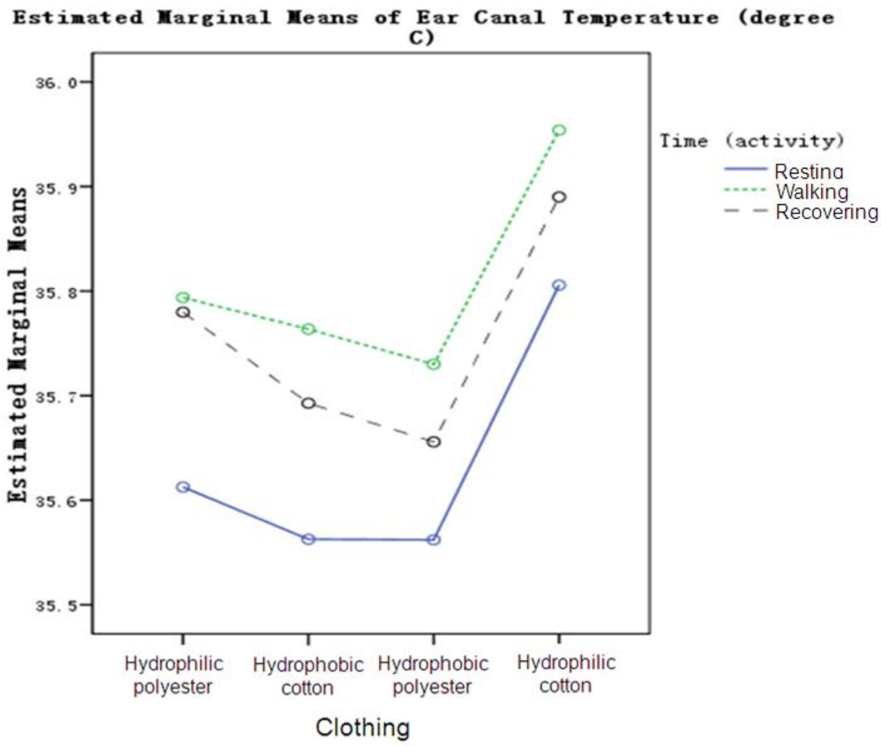


(c)

Figure 6-10 Estimated marginal means of ear canal temperature wearing different clothing (a), in different time (activity) (b), and wearing clothing during different activity (c)

Post Hoc analysis shows that ear canal temperature in hydrophilic cotton group is significantly higher than in others garment groups ($p<0.05$) (Figure 6-10).

These findings suggest that wearing hydrophilic cotton induce higher thermal stress in hot climate during running than wearing any other fabric (hydrophobic cotton, hydrophilic polyester, and hydrophobic polyester).

In 32°C, and 50% RH, heat release by conduction is not efficient as the temperature gradient between the skin and environment is small. In this condition, heat loss by evaporation plays a major role in heat exchange of human body. The sweating wets the hydrophilic cotton fabric thus increasing its air resistance

(Appendix IV). Therefore, a barrier of inside moisture transport from microclimate to outer environment is created. Then, higher heat stress is induced.

6.3.7 Mean skin temperature

Mean skin temperature plays an important role in heat exchange of human body from conduction, convection, and radiant exchange. It is found that mean skin temperature decreases in all four groups after running. It is presumed that this decrease is due to the strong heat loss on skin by sweating after running in hot environment. It is found that both Clothing ($F=5.599$, $p<0.01$) and Time (activity) ($F=43.780$, $p<0.001$) had significant effects on mean skin temperature, probably because different fabrics influence heat exchange of human body by their different transport capability. A significant Clothing by Time (activity) interaction effects also has been noted ($F=2.932$, $p<0.05$) (Table 6-8).

Table 6-8 Effects of Clothing and Time (activity) on mean skin temperature

Tests of Within-Subjects Effects						
Effects		**Type III Sum of Squares**	**df**	**F**	**Sig.**	
Clothing	Sphericity Assumed	17.531	3	5.599	0.002	**
Time (activity)	Huynh-Feldt	73.036	1.608	43.780	0.000	***
Clothing * Time(Activity)	Greenhouse-Geisser	7.522	3.472	2.932	0.033	*

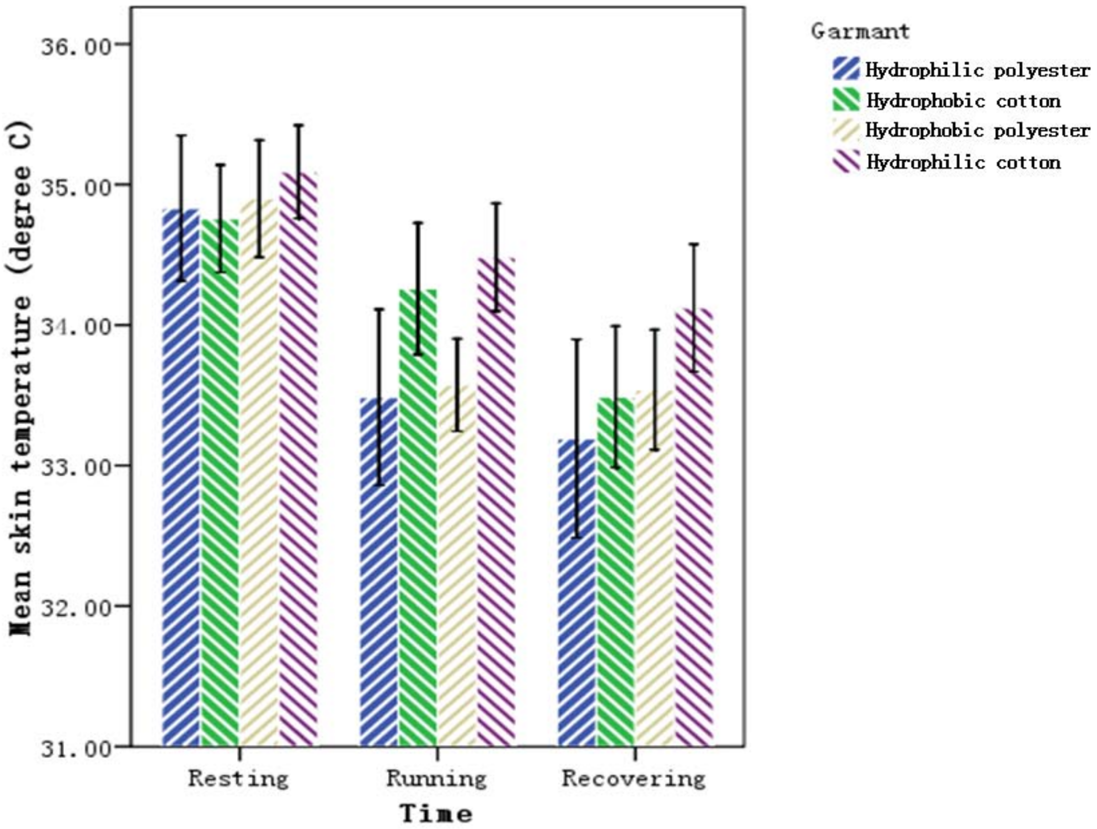
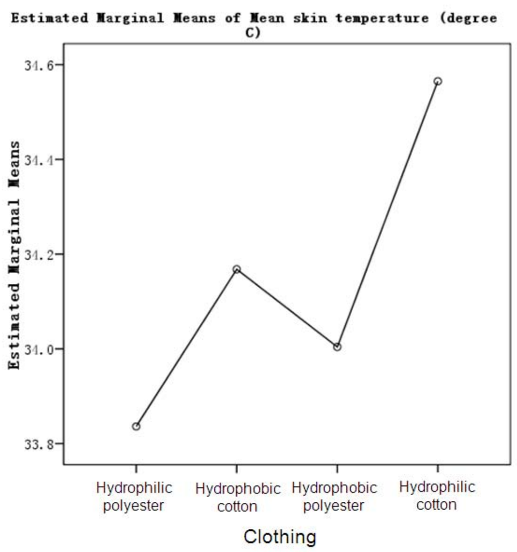
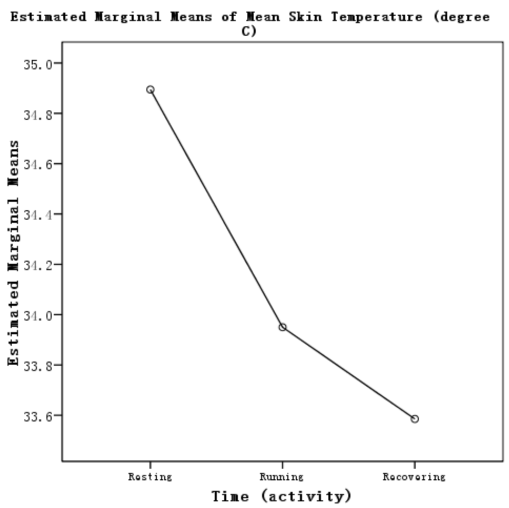


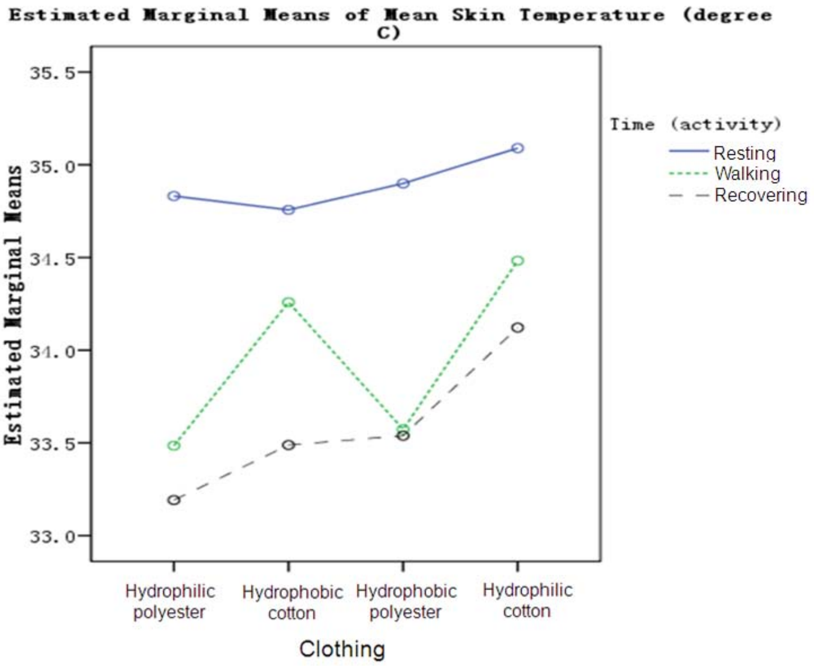
Figure 6-11 Mean skin temperature





(b)

(a)



(c)

Figure 6-12 Estimated marginal means of skin temperature wearing different clothing (a), in different time (activity) (b), and wearing clothing during different activity (c)

Skin mean temperature in hydrophilic cotton groups is higher than polyester groups during running ($p<0.05$); and, skin mean temperature in hydrophilic cotton group is significantly higher than in hydrophilic polyester group ($p<0.05$) during recovering. It implies that fabric transfer properties play important roles in heat exchange during running and recovering in hot climates.

6.3.8 Skin-clothing microclimate absolute humidity

Skin-clothing microclimate absolute humidity reflects the moisture content between skin and clothing during wearing different materials and treatment clothing in hot condition. It shows an increasing pattern from resting to running and recovering. This suggests the moisture accumulation occurs in the microclimate because of the increased production of sweating during running and recovering.

Analysis of results shows that Clothing ($F=7.116$, $p<0.001$) and Time (activity) ($F=32.061$, $p<0.001$) have significant effects on microclimate absolute humidity (Table 6-9).

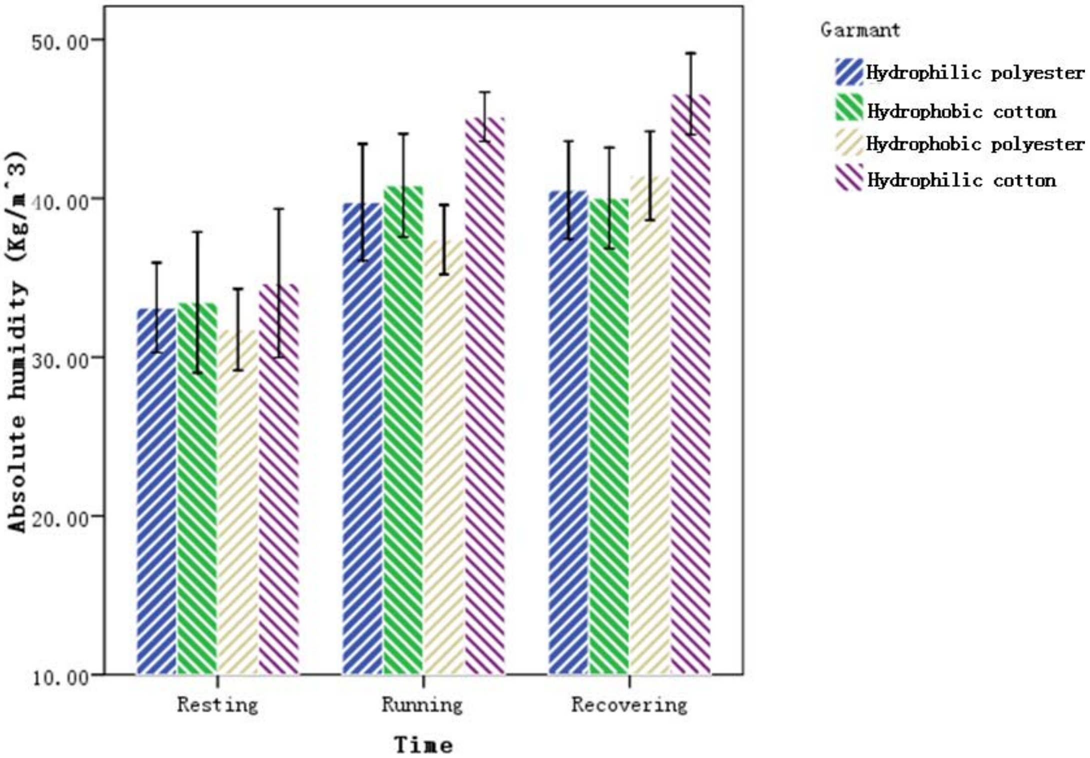
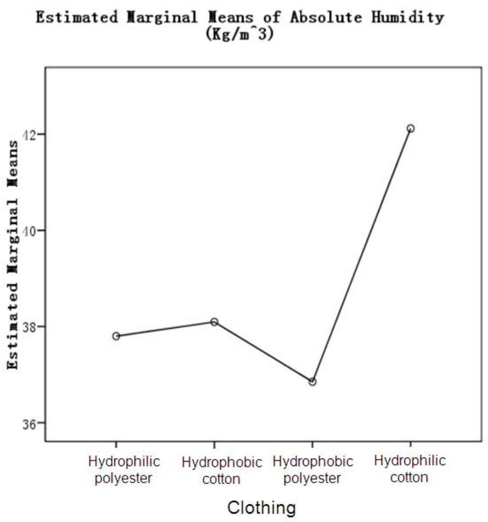


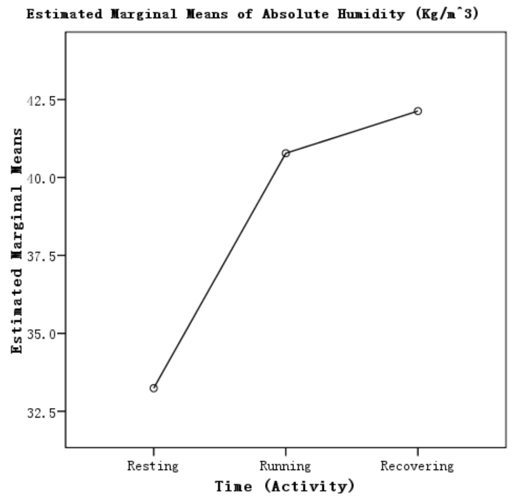
Figure 6-13 Microclimate absolute humidity during resting, running and recovering

Table 6-9 Effects of Clothing and Time (activity) on microclimate absolute humidity

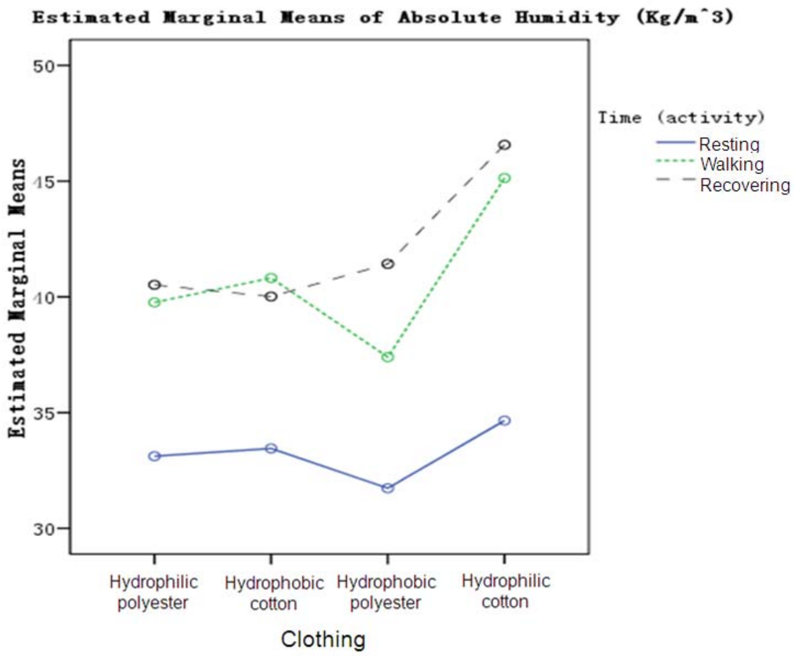
Tests of Within-Subjects Effects						
Effects		Type III Sum of Squares	df	F	Sig.	
Clothing	Sphericity Assumed	976.789	3.000	7.116	0.000	***
Time (activity)	Greenhouse-Geisser	3673.268	1.367	32.061	0.000	***
Clothing * Time(Activity)	Greenhouse-Geisser	283.493	3.572	2.164	0.089	



(a)



(b)



(c)

Figure 6-14 Estimated marginal means of mean skin temperature wearing different clothing (a), in different time (activity) (b), and wearing clothing during different activity (c)

Microclimate absolute humidity in hydrophilic cotton group is higher than polyester clothing groups during running ($p<0.05$) (Fig. 6-14 (c)). Additionally, it is higher than other three groups during recovering ($p<0.05$).

6.3.9 Clothing surface temperature

Clothing surface, the outside of the body-skin-clothing system, its temperature provides information of the heat release from the human body reached the interface of fabric and environment. Fig 6-15 suggests that clothing surface temperature decreased after running implying the role of strong sweating evaporation in heat release in hot weather.

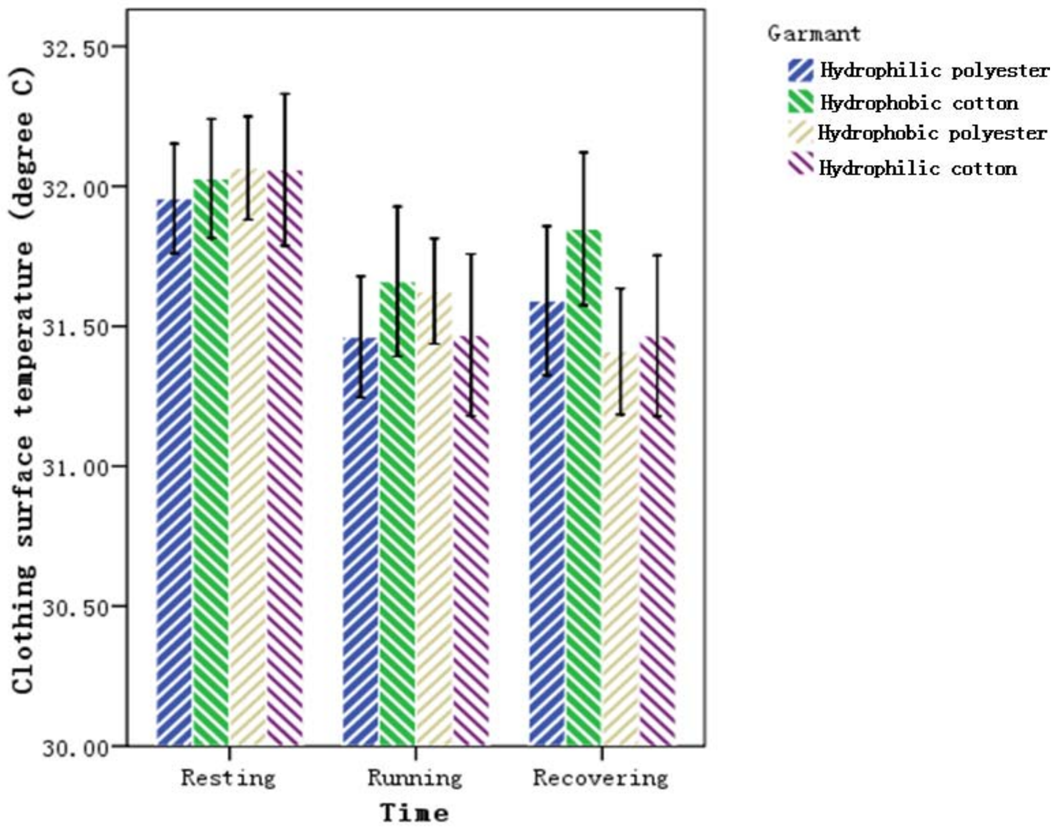


Figure 6-15 Clothing surface temperature

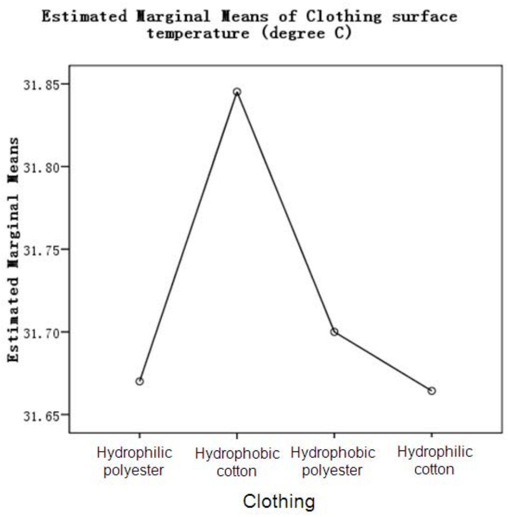
Table 6-10 Effects of Clothing and Time (activity) on clothing surface temperature

Tests of Within-Subjects Effects						
Effects		**Type III Sum of Squares**	**df**	**F**	**Sig.**	
Clothing	Sphericity Assumed	1.301	3	1.887	0.142	
Time (activity)	Greenhouse-Geisser	11.345	1.521	10.586	0.001	**
Clothing * Time(Activity)	Greenhouse-Geisser	1.769	3.105	2.500	0.066	

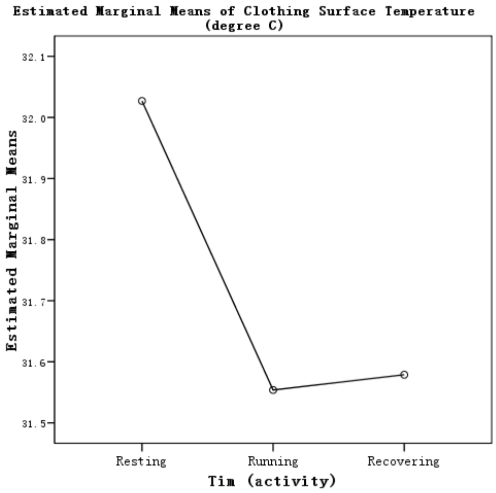
Time (activity) significantly influences clothing surface temperature ($F=10.586$, $p<0.01$), which can be understood as the role of sweating evaporation and heat exchange. A Clothing by Time (activity) interaction effect has been found at significant level of $p=0.066$ ($F=2.500$, $p=0.066$) (Table 6-10).

Clothing surface temperature in hydrophobic cotton group is higher than hydrophobic polyester group ($p<0.05$), and hydrophilic cotton groups ($p<0.05$), suggesting that hydrophobic cotton fabric can transfer heat from inside to outside in such a strong manner as to release heat, which may be helpful to reduce heat stress during recovering.

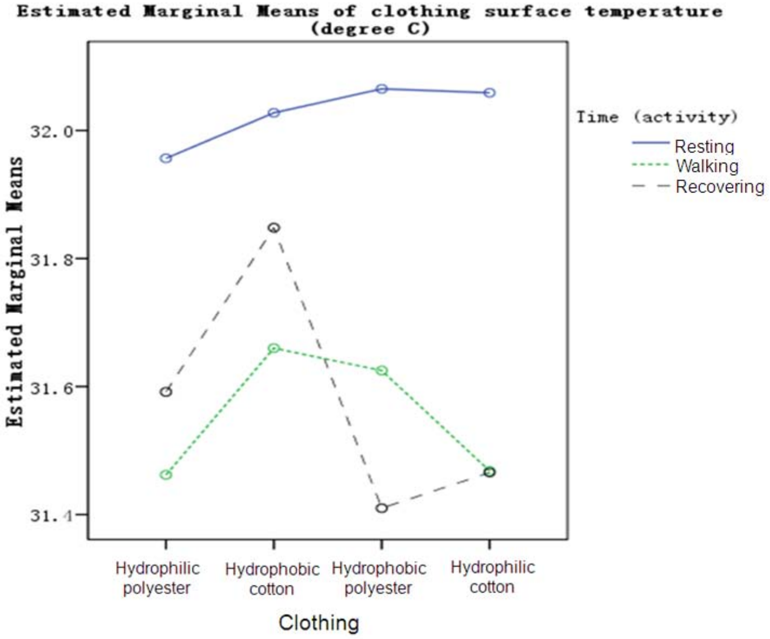
As interpreted in section 6.3.6, in 32°C, and 50% RH, heat loss by conduction is restrained, and heat loss by evaporation may play the main role in heat exchange of in human body. The sweating, which has wetted hydrophilic cotton fabric, and increased air resistance, may indeed inhibit evaporation from inside microclimate to outer environment, inducing higher clothing surface temperature.



(a)



(b)



(c)

Figure 6-16 Estimated marginal means of clothing surface temperature wearing different clothing (a), in different time (activity) (b), and wearing clothing during different activity (c)

Summary

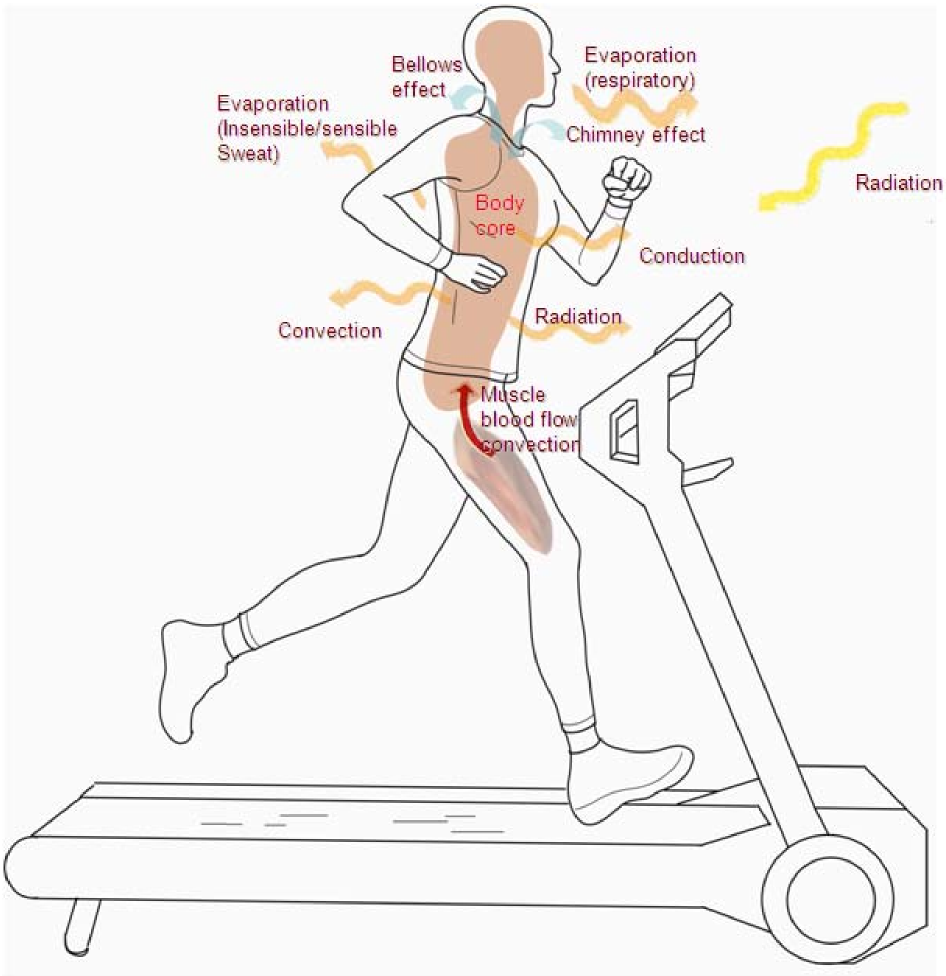


Figure 6-17 Illustration of heat exchange during exercise

In hot environments, without strong ventilation, skin water evaporation in polyester groups is higher than in cotton groups during resting and recovering. This suggests heat release in polyester groups is stronger than in cotton groups because evaporation is the most important way to release heat during exercise (Brotherhood 2008) in hot condition (Arens et al. 2006). Higher skin water evaporation in polyester group moisturizes stratum corneum, because of more water vapor from inner layer skin to outer layer releasing heat. With the continued increase in skin evaporation during running in hot environment, sweating does occur. SCWC archived saturation around 100% due to its swelling mechanism.

Microclimate humidity in hydrophilic cotton group is higher than other groups indicating that the skin evaporation may have accumulated in hydrophilic cotton group; while polyester groups and hydrophobic cotton group with lower microclimate humidity levels suggest that evaporation occurs more effectively in these fabrics.

Skin temperature in cotton groups was higher than in polyester groups during running implying more heat accumulation in microclimate. Due to higher air resistance property of cotton fabric, evaporation in cotton groups is weak, heat is accumulated in microclimate, inhibits release and increases skin temperature. During recovering, as hydrophobic cotton did not absorb liquid sweating, the evaporation process is effective, and skin temperature is lower than in hydrophilic cotton group.

The heat accumulation in hydrophilic cotton group thus induces higher ear canal temperature in this study.

The quick increase in heart rate in polyester groups rather than in cotton groups during start of running suggests automatic nervous system becomes active faster in polyester groups than in cotton groups. This may imply the benefit of polyester fabric in sportswear application.

Hypotheses *III* and *IV* have been verified as:

- *Clothing **influences** thermal physiology of human body in terms of core temperature and skin temperature in hot environment arising from its influence on heat release process of human body.*

- ***Clothing* influence *SCWC and TEWL in hot environment by affecting heat and moisture and liquid water transport between human body and clothing.***

After obtaining the above results from statistical analysis, relationships between fabric properties and skin physiology and mechanisms were explored by Hierarchical Linear Regression as presented below.

6.4 Mechanism exploration by Hierarchical Linear Regression

6.4.1 Skin water evaporation

Table 6-11 presents skin water evaporation, which significantly correlates with fabric hygroscopic property, fabric transport capability and shearing resistance, SCWC, skin-clothing microclimate humidity, skin mean temperature, and clothing surface temperature in hot environment.

Table 6-11 Correlation of skin water evaporation with fabric properties

Pearson Correlation	1	2	3	4	5	6	7
1 Skin water evaporation							
2 Hygroscopicity	0.19**						
3 SCWC	0.55***	0.17*					
4 Transport capability	0.19**	0.83***	0.13*				
5 Skin mean temperature	-0.26***	-0.10	-0.33***	-0.16*			
6 Clothing surface temperature	-0.23*	-0.08	-0.28***	-0.02	0.30***		
7 Skin-clothing microclimate humidity	0.26***	-0.07	0.45***	-0.09	-0.49***	-0.42***	
8 Shearing resistance	0.16*	0.88***	0.15***	0.86***	-0.09	-0.08	-0.03

Results from Hierarchical Linear Regression shown in Table 6-12 indicates that fabric hygroscopicity properties and SCWC are two strong predictors of skin water evaporation. In comparison with cotton fabric, polyester fabric has a positive effect on skin water evaporation in hot environment. Meanwhile, SCWC has a positive effect on skin water evaporation too. Model 2 was selected to describe the relation between skin water evaporation and fabric physical properties and SCWC.

Table 6-12 Hierarchical Linear Regression results for skin water evaporation prediction

Model		Coefficients(a)			Modeling			
		Standardized Coefficients Beta	t	Sig.	R Square	F Change	Sig. F Change	
1	Hygroscopicity (hygroscopic=0)	0.19	2.42	0.02	0.04	5.83	0.02	*
2	Hygroscopicity (hygroscopic=0)	0.10	1.44	0.15	0.31	62.12	0.00	***
	SCWC	0.53	7.88	0.00				

a Dependent Variable: Skin water evaporation

6.4.2 SC water content

SC water content significantly correlates with fabric hygroscopicity, skin water evaporation, skin mean temperature, Time (activity), skin-clothing microclimate humidity, clothing surface temperature and fabric shearing resistance, as well as transport capability (Table 6-13).

Table 6-13 Correlation of SCWC and fabric properties

Correlations								
Pearson Correlation	1	2	3	4	5	6	7	8
1 SCWC	1							
2 Hygroscopicity (hygroscopic=0)	0.17*	1						
3 Skin water evaporation	0.55***	0.19**	1					
4 Skin mean temperature	-0.33***	-0.10	-0.26***	1				
5 Skin-clothing microclimate humidity	0.45***	-0.07	0.26***	-0.49***	1			
6 D_Time1 (resting=1)	-0.49***	0.00	-0.27***	0.54***	-0.62***	1		
7 Shearing resistance	0.15*	0.88***	0.16*	-0.09	-0.03	0.00	1	
8 Transprot capability	0.13*	0.83***	0.19**	-0.16*	-0.09	0.00	0.86***	1
9 Clothing surface temperature	-0.28***	-0.08	-0.23**	0.30***	-0.42***	0.40***	-0.08	-0.02

The results of the Hierarchical Linear Regression shown in Table 6-14 suggests that fabric hygroscopicity properties, skin mean temperature, Time (activity), and skin-clothing microclimate humidity are the four strong predictors of SCWC. When compared with cotton fabric, polyester fabric has a positive effect on SCWC in hot environment. Skin mean temperature and skin-clothing microclimate humidity has a positive effect on SCWC, while activities of resting (Time (resting=1)) has a negative effect on SCWC compared with recovering after running. Model 4 was selected to describe the relation between SCWC and fabric physical properties, activities, microclimate humidity, and skin mean temperature in hot environment.

Table 6-14 Hierarchical Linear Regression results for SCWC prediction

Model		Coefficients(a)			Modeling			
		Standardized Coefficients Beta	t	Sig.	R Square	F Change	Sig. F Change	
1	Hygroscopicity (hygroscopic=0)	0.17	2.20	0.03	0.03	4.83	0.03	*
2	Hygroscopicity (hygroscopic=0)	0.06	0.92	0.36	0.34	8.50	0.00	**
	Skin mean temperature	-0.20	-2.92	0.00				
3	Hygroscopicity (hygroscopic=0)	0.11	1.72	0.09	0.42	19.83	0.00	***
	Skin mean temperature	-0.05	-0.69	0.49				
	Skin-clothing microclimate humidity	0.32	4.45	0.00				
4	Hygroscopicity (hygroscopic=0)	0.11	1.83	0.07	0.46	12.08	0.00	***
	Skin mean temperature	0.03	0.46	0.64				
	Skin-clothing microclimate humidity	0.20	2.49	0.01				
	D_Time1 (resting=1)	-0.28	-3.48	0.00				

a Dependent Variable: SCWC

6.4.3 Ear canal temperature

Table 6-15 Correlation of ear canal temperature between fabric properties

Correlations									
Pearson Correlation	1	2	3	4	5	6	7	8	9
1 Ear canal temperature									
2 Hygroscopicity (hygroscopic=0)	-0.15*								
3 Hydrophilicity (hydrophilic=0)	-0.24***	0.00							
4 D_Time1 (resting=1)	-0.23**	0.00	0.00						
5 Shearing resistance	-0.04	0.88***	-0.45***	0.00					
6 Transport capability	-0.17**	0.83***	-0.07	0.00	0.86***				
7 Clothing surface temeprature	-0.06	-0.06	0.09	0.39***	-0.08	-0.02			
8 Skin mean temperature	-0.08	-0.19**	-0.05	0.45***	-0.17**	-0.22***	0.25***		
9 Skin-clothing microclimate humidity	0.22***	-0.10	-0.13*	-0.57***	-0.04	-0.11*	-0.38***	-0.38***	
10 D_Time2 (running=1)	0.18**	0.00	0.00	-0.5***	0.00	0.00	-0.21	-0.12	0.19**

Correlation matrix shows the Pearson correlation and the significance of each variable (Table 6-15). Ear canal temperature correlates with fabric materials and treatment, Time (activity), fabric transport capability, skin-clothing microclimate humidity at the 0.05 level or higher. Ear canal temperature did not correlate with clothing surface temperature and skin mean temperature.

The Hierarchical Linear Regression results to predict change in ear canal temperature, in this study, are described in Table 6-16. Fabric materials and treatment of pajamas and Time (activity) are three strong predictors of ear canal temperature in hot environment. Hydrophobic treatment of fabric has a negative effect on ear canal temperature compared with hydrophilic clothing (reference variable). And, polyester fabric also has a negative effect on ear canal temperature compared with cotton clothing (reference variable). Activities (resting) have a negative effect on ear canal temperature when compared with the same during running and recovering. It is due to the fact that sweating has occurred during running and recovering, which has reduced skin temperature. The model 3 was selected to describe the relationship.

Table 6-16 Hierarchical Linear Regression results of ear canal temperature prediction

Model		Coefficients(a)			Modeling			
		Standardized Coefficients Beta	t	Sig.	R Square	F Change	Sig. F Change	
1	Hygroscopicity (hygroscopic=0)	-0.15	-2.34	0.02	0.02	5.48	0.02	*
2	Hygroscopicity (hygroscopic=0)	-0.15	-2.41	0.02	0.08	15.34	0.00	***
	Hydrophilicity (hydrophilic=0)	-0.24	-3.92	0.00				
3	Hygroscopicity (hygroscopic=0)	-0.15	-2.48	0.01	0.14	14.81	0.00	***
	Hydrophilicity (hydrophilic=0)	-0.24	-4.03	0.00				
	D_Time1 (resting=1)	-0.23	-3.85	0.00				

a Dependent Variable: Ear canal temperature

6.4.4 Skin-clothing microclimate humidity

Table 6-17 Correlation of skin-clothing microclimate humidity and fabric properties

Correlations										
	Pearson Correlation	1	2	3	4	5	6	7	8	9
1	Skin-clothing microclimate humidity									
2	D_Time1 (resting=1)	-0.57***								
3	Clothing surface temperature	-0.38***	0.39***							
4	Hygroscopicity (hygroscopic=0)	-0.10*	0.00	-0.06						
5	Hydrophilicity (hydrophilic=0)	-0.13*	0.00	0.09	0.00					
6	Skin mean temperature	-0.38***	0.45***	0.25***	-0.19**	-0.05				
7	D_Time2 (running=1)	0.19**	-0.50***	-0.21	0.00	0.00	-0.12*			
8	Transprot capability	-0.11*	1.23	-0.02	0.83***	-0.07	-0.22***	0.00		
9	Shearing resistance	-0.04	1.53	-0.08	0.88***	-0.45***	-0.17**	0.00	0.86***	
10	OMMC	0.16**	0.00	-0.09	-0.23***	-0.95***	0.11*	0.00	-0.25***	0.18**

Table 6-17 shows that skin-clothing microclimate humidity significantly correlates with fabric materials and treatment, Time (activity), clothing surface temperature, fabric transport capability and moisture management properties as well as skin mean temperature at the 0.05 level or higher.

Table 6-18 Hierarchical Linear Regression results for microclimate humidity prediction

Model		Coefficients(a)			Modeling			
		Standardized Coefficients Beta	t	Sig.	R Square	F Change	Sig. F Change	
1	D_Time1 (resting=1)	-0.57	-10.72	0.00	0.33	114.84	0.00	***
2	D_Time1 (resting=1)	-0.50	-8.82	0.00	0.35	10.79	0.00	**
	Clothing surface temperature	-0.19	-3.28	0.00				
3	D_Time1 (resting=1)	-0.50	-8.83	0.00	0.37	5.02	0.03	*
	Clothing surface temperature	-0.19	-3.46	0.00				
	Hygroscopicity (hygroscopic=0)	-0.12	-2.24	0.03				
4	D_Time1 (resting=1)	-0.50	-8.97	0.00	0.38	4.40	0.04	*
	Clothing surface temperature	-0.18	-3.25	0.00				
	Hygroscopicity (hygroscopic=0)	-0.12	-2.24	0.03				
	Hydrophilicity (hydrophilic=0)	-0.11	-2.10	0.04				
5	D_Time1 (resting=1)	-0.42	-7.04	0.00	0.41	10.39	0.00	**
	Clothing surface temperature	-0.17	-3.04	0.00				
	Hygroscopicity (hygroscopic=0)	-0.15	-2.91	0.00				
	Hydrophilicity (hydrophilic=0)	-0.12	-2.34	0.02				
	Skin mean temperature	-0.19	-3.22	0.00				

a Dependent Variable: Skin-clothing microclimate humidity

The results of the Hierarchical Linear Regression to predict change in skin-clothing microclimate humidity are shown in Table 6-18. Fabric materials and treatment, Time (activity), skin mean temperature and clothing surface temperature were five strong predictors of skin-clothing microclimate humidity in hot environment. Hydrophobic treatment of fabric has a negative effect on skin-clothing microclimate humidity compared with hydrophilic clothing. Moreover, polyester fabric also has a negative effect on skin-clothing microclimate humidity compared with cotton clothing. Time (activity) has a negative effect on skin-clothing microclimate humidity in that it is lower during resting (reference variable) compared with the humidity recorded during running and recovering. Clothing surface temperature also has a negative effect on skin-clothing microclimate humidity. Skin mean temperature has a negative effect on clothing-skin microclimate humidity. The model 5 was selected to describe the relationship.

6.4.5 Clothing surface temperature

Table 6-19 Correlation of clothing surface temperature and fabric properties

Correlations									
Pearson Correlation	1	2	3	4	5	6	7	8	9
1 Clothing surface temperature									
2 D_Time1 (rest=1)	0.39***								
3 Skin-clothing microclimate humidity	-0.38***	-0.57***							
4 Skin mean temperature	0.25***	0.45***	-0.38***						
5 D_Time2 (running=1)	-0.21***	-0.50***	0.19**	-0.12*					
6 Hydrophilicity (hydrophilic=0)	0.09	0.00	-0.13*	-0.05	0.00				
7 Shearing resistance	-0.08	0.00	-0.04	-0.17**	0.00	-0.45***			
8 Transprot capability	-0.02	0.00	-0.11	-0.22***	0.00	-0.07	0.86***		
9 OMMC	-0.09	0.00	0.16**	0.11	0.00	-0.95***	0.18**	-0.25***	
10 Hygroscopicity (hygroscopic=0)	-0.06	0.00	-0.10*	-0.19	0.00	0.00	0.88***	0.83***	-0.23***

From Table 6-19, it is seen that clothing surface temperature significantly correlated with Time (activity), skin-clothing microclimate humidity and skin mean temperature, at the 0.05 level or higher.

Table 6-20 Hierarchical Linear Regression results for clothing surface temperature prediction

Model	Coefficients(a)			Modeling			
	Standardized Coefficients Beta	t	Sig.	R Square Change	F Change	Sig. F Change	
1 D_Time1 (rest=1)	0.39	6.46	0.00	0.15	41.78	0.00	***
2 D_Time1 (rest=1)	0.25	3.54	0.00	0.19	10.79	0.00	**
Skin-clothing microclimate humidity	-0.23	-3.28	0.00				

a Dependent Variable: Clothing surface temperature

The results of the Hierarchical Linear Regression to predict change in clothing surface temperature are shown in Table 6-20. Time (activity) and skin-clothing microclimate humidity were two strong predictors of skin-clothing microclimate humidity in hot environment. Activities (resting=1) have a positive effect on clothing surface temperature which indicated that clothing surface temperature during running and recovering is lower than during resting. Meanwhile, skin-clothing microclimate humidity has a negative effect on clothing surface temperature. Model 2 was selected to describe the relationship.

6.4.6 Skin mean temperature

Table 6-21 Correlation of skin mean temperature and fabric properties

Correlations									
Pearson Correlation	1	2	3	4	5	6	7	8	9
1 Skin mean temperature									
2 D_Time1 (resting=1)	0.45***								
3 Skin-clothing microclimate humidity	-0.38***	-0.57***							
4 Shearing resistance	-0.17**	0.00	-0.04						
5 Transport capability	-0.22***	0.00	-0.11*	0.86***					
6 D_Time2 (running=1)	-0.12*	-0.50***	0.19**	0.00	0.00				
7 Clothing surface temperature	0.25***	0.39***	-0.38***	-0.08	-0.02	-0.21***			
8 Hygroscopicity (hygroscopic=0)	-0.19**	0.00	-0.10	0.88***	0.83***	0.00	-0.06		
9 Hydrophilicity (hydrophilic=0)	-0.05	0.00	-0.16*	-0.45***	-0.07	0.00	0.09	0.00	
10 OMMC	0.11*	0.00	0.16**	0.18**	-0.25***	0.00	-0.09	-0.23***	-0.95***

From Table 6-21, it is clear that skin mean temperature significantly correlates with Time (activity), skin-clothing microclimate humidity, fabric material, fabric shearing resistance, transport capability, moisture management properties, and skin mean temperature, at the 0.05 level or higher.

Table 6-22 Hierarchical Linear Regression results for skin mean temperature prediction

Model	Coefficients(a)			Modeling			
	Standardized Coefficients Beta	t	Sig.	R Square	F Change	Sig. F Change	
1 D_Time1 (resting=1)	0.45	7.80	0.00	0.20	60.83	0.00	***
2 D_Time1 (resting=1)	0.34	4.94	0.00	0.23	7.34	0.01	**
Skin-clothing microclimate humidity	-0.19	-2.71	0.01				
3 D_Time1 (resting=1)	0.34	4.94	0.00	0.26	9.61	0.00	**
Skin-clothing microclimate humidity	-0.20	-2.92	0.00				
Shearing resistance	-0.17	-3.10	0.00				
4 D_Time1 (resting=1)	0.32	4.71	0.00	0.29	10.94	0.00	**
Skin-clothing microclimate humidity	-0.24	-3.48	0.00				
Shearing resistance	0.13	1.21	0.23				
Transport capability	-0.36	-3.31	0.00				

a Dependent Variable: skin mean temperature

The results of the Hierarchical Linear Regression to predict change in clothing surface temperature, as shown in Table 6-22, indicates Time (activity), skin-clothing microclimate humidity, fabric transport capability, and shearing resistance are four strong predictors of skin mean temperature in hot environment. Activities (resting=1) show a positive effect on skin mean temperature indicating that clothing surface temperature during running and recovering is lower than during resting due to sweating that occurred during running. Meanwhile, skin-clothing microclimate humidity has a positive effect on clothing surface temperature because higher microclimate humidity may inhibit skin evaporation, recue heat release, and thus increase skin temperature. Fabric shearing resistance has a positive effect on skin mean temperature suggesting high shearing and surface roughness arising from poor deformation of fabric and more static air held, blocking heat release from microclimate to outside thus inducing higher skin temperature. Fabric transport capability has a negative effect on skin mean temperature because high transport capability enhances heat release from insider of human body to outside, reduces heat stress, and skin temperature. Model 4 was selected to describe the relationship.

6.5 Discussion and conclusions

Table 6-23 Summaries of models of effects of clothing on skin physiology

Factors	Skin water evaporation	SCWC	Ear canal temperature	Skin-clothing microclimate humidity	Skin mean temperature	Clothing surface tempreature
D_Time1 (resting=1)	-	-	-	-	+	+
Hygroscopicity (hygroscopic=0)	+	+	-	-		
Hydrophilicity (hydrophilic=0)			-	-		
Shearing resistance					+	
Transport capability					-	
Skin-clothing microclimate humidity		+			-	-
Skin mean temperature		+		-		
Clothing surface temperature				-		

Interactions of fabric, skin physiology, and thermal physiology in hot environment during different activities are summarized in Table 6-23 and Fig. 6-18. Fig. 6-18 illustrates pathway of heat generation during running in hot condition. Running in hot condition increases heat accumulation in human body, increases core temperature, skin evaporation and stratum coreneum water content, as well as increases microclimate humidity between skin and fabric. Properties of fabric influence the human heat regulation via their impacts on heat release, then, affect microclimate humidity, skin evaporation, stratum corneum water content, and skin and core temperature (Fig. 6-19). In this study, it is found that clothing surface temperature is influenced by microclimate humidity between skin and clothing, which suggests that evaporation mechanism may play a key role in heat release in hot condition.

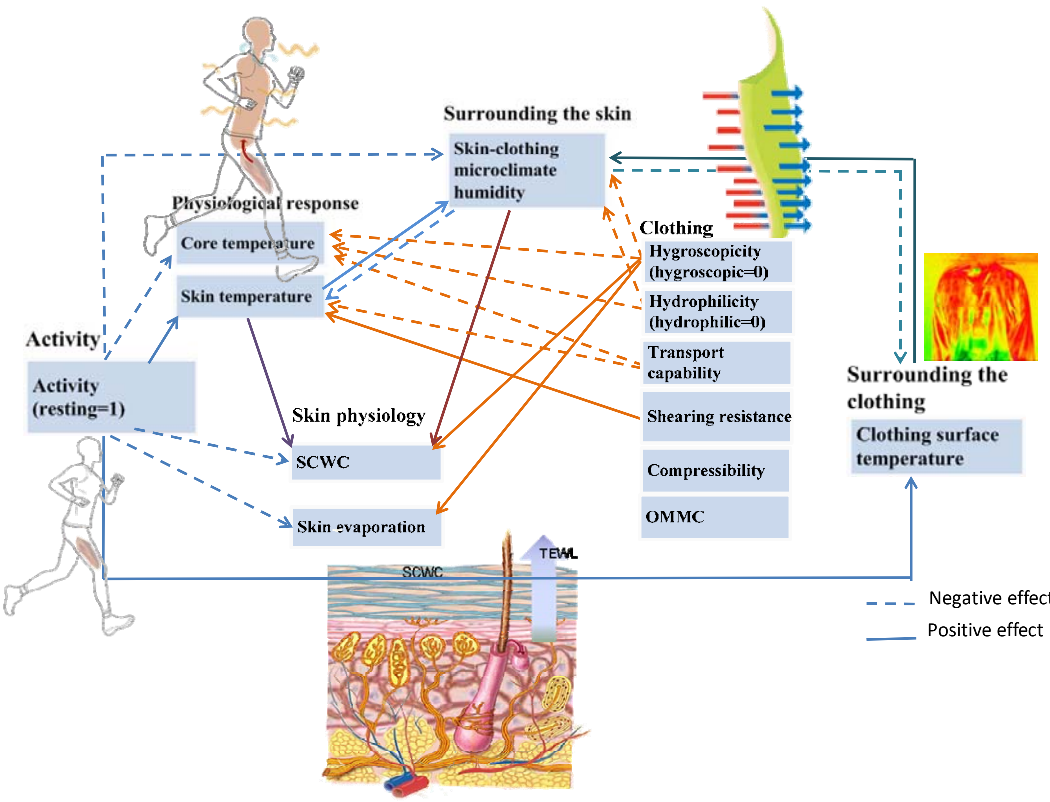


Figure 6-18 Clothing-wearer interactions of skin physiology and thermal physiology in activities in hot condition

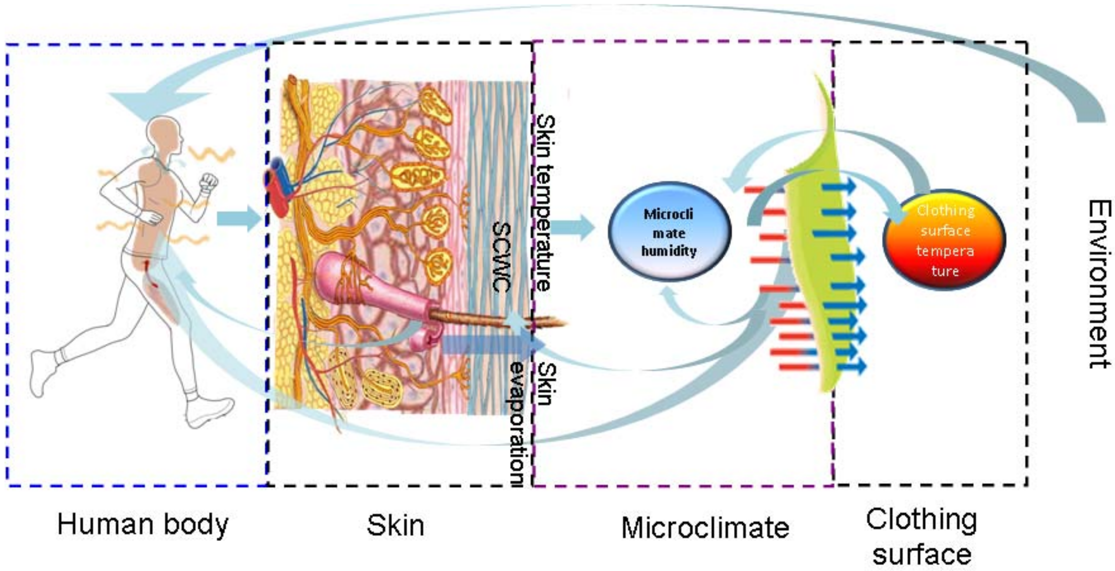


Figure 6-19 Effects of fabric on skin physiology in hot condition

In Fig. 6-19, presents the fact that there is a reduction in ear canal temperature and microclimate absolute humidity during running in hot environment. Hydrophobic fabric rescues core temperature and microclimate humidity. Fabric with strong transport capability (air permeability, thermal conductivity, and water vapor permeability) helps heat release from human body to environment, and reduces heat stress. Fabric with higher shearing resistance means relatively stable fabric structure and rough fabric surface, which would reduce heat release during running.

The hypotheses *III* and *IV* are verified as:

- *Clothing **impacts on** heat evaporation process of human body in hot condition, and **influences** thermal physiology of human body such as **core temperature and skin temperature** .*
- *Clothing **influences** evaporation heat loss process of human body by **affecting moisture and heat transport, which in turn affect** skin water evaporation and stratum corenum water content.*

Chapter 7 Effects of Ultraviolet Protective Clothing on Skin Physiological Response

7.1 Introduction

In the previous chapters, effects of clothing on skin physiology in mildly cold condition and hot conditions were studied. Clothing-wearer interaction in skin physiology, sensory response, neural psychological response and thermal physiology has been described. To achieve the sixth objective, which pertained to studying the effects of UV blocking fabric on skin physiology under solar exposure, of this study, this chapter, a parallel wear trial designed to investigate the effects of UV blocking fabric on skin physiology under solar exposure Both cutaneous and immunological response under solar exposure will be reported.

Hong Kong is located at 22°08' to 22°35' N, 113°49' to 114°31' E. The mean daily global solar radiation has been recorded around12.72 MJ/m^2 in the past decade (Observatory 2006). Hong Kong's inhabitants have been exposed to this degree of solar radiation for a long time. What physiological responses might, therefore, have occurred as a result of many years of exposure to high solar radiation?

Cutaneous, stress and fatigue symptom responses of solar exposure of Hong Kong inhabitants were studied. The roles of UV blocking fabric were investigated. Hypothesis *VII* was verified by wear trial carried out under solar exposure.

Hypothesis VII

<u>UV blocking properties of clothing may influence on SCWC, TEWL, skin melanin content, erythemal level and immunological response under acute solar exposure.</u>

7.2 Experimental information

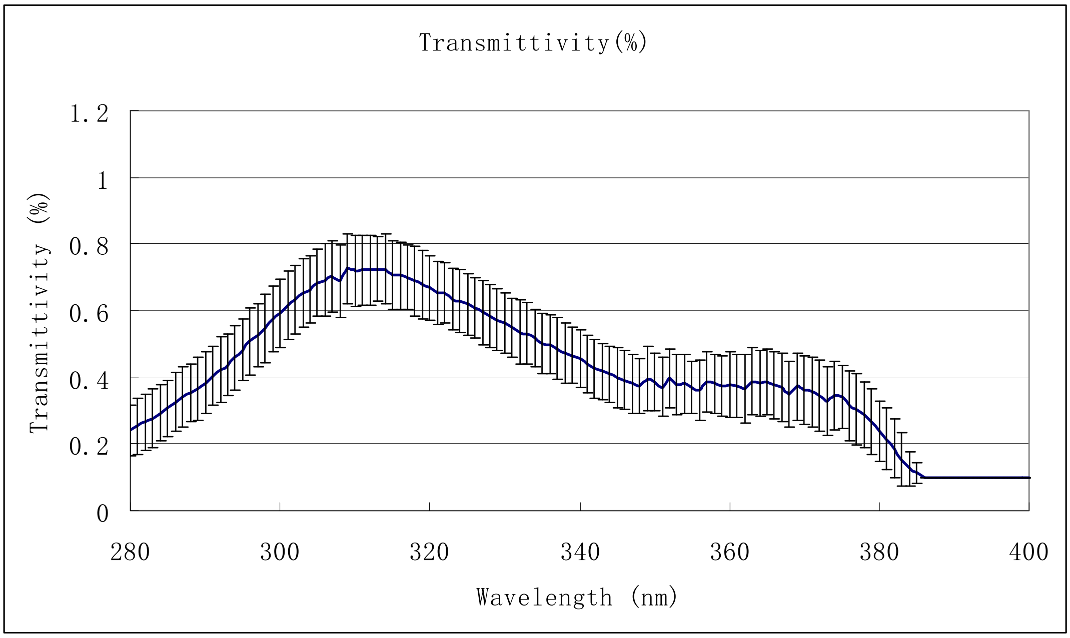
7.2.1 Materials

The physical properties of the experimental fabric

Pure cotton fabric with a UV blocking function (UPF=32.97±2.28) was applied in the study. Detailed physical properties of the fabric are summarized in Table 7-1. The UV blocking properties of the fabric were relatively good, with the ability to block over 99% of UVA and UVB radiation (Fig. 7-1)[4].

Table 7-1 Physical properties of the UV protective fabric (Mean±STD)

Fibuer content	**Color**	**Fabric structure**	**Tex (weft/warp)**	**UPF**
100% cotton	White	Plain woven	14.1/14.1	32.97±2.28
Density (cm) (weft/warp)	**Fabric weight (g/m^2)**	**Clothing cover**	**Thickness (mm)**	
28/52	123±0.08	0.84±0.5	0.32±0.03	



[4] following standard Australian/ New Zealand Standard AS/NZS 4399:1996

Figure 7-1 Spectrum of the UV blocking fabric applied in the experiment

7.2.2 Questionnaires

Two questionnaires were designed. One (Questionnaire I) was designed to obtain subjects' basic information, such as age, weight, height, health status, incidence of skin disease. Questionnaire II focused on fatigue symptoms, developed by the Japan Society for Occupational Health (Yoshitake 1971). The questionnaire on subjective fatigue consists of 3 dimensions: Fatigue I (drowsiness and dullness), Fatigue II (difficulty in concentration), and Fatigue III (projection of disintegration). Each dimension has ten statements in a nine points scale.

7.2.3 Measurements

UV radiation intensity was measured by UV-B (MS-210W, EKO Inst.), and UV-A (MS-210A, EKO Inst.). The fabric's UPF value was measured by a Varian Cary 300 UV-VIS Spectrophotometer (Varian, USA). A Cutometer MPA® 580 (CK, Germany) was used to measure the melanin content of the skin; a Mexameter® MX18 to measure the erythema level; a Corneometer® CM825 to measure the stratum corneum water content; and a Tewameter® TM300 to measure transepidermal water loss.

Urinary free catecholamines were tested in order to record stress levels during the experimental period. Urine was collected before and after exposure to the sun, with hydrochloric acid (6N, 0.2ml) (preservative) being added to 30ml urine samples, which were then stored at -80°C. Separation was performed by column EICOMPAK CA-5ODS (2.1mmID x 150mm). The mobile phase contained a 88% 0.1M phosphate buffer pH6.0, methanol 12% (HPLC, 99.9% Aldrich), sodium octanesulfonate (Aldrich) 600mg/L, and 50mg/L EDTA.2Na. Flow rate was 0.23ml/min. Standard adrenaline, noradrenaline, dopamine, dehydroxy benzylamine (DHBA, internal standard, Sigma) were obtained from Sigma (St. Louis, Mo. USA).

7.2.4 Methods

The experimental protocol was approved by the Hong Kong Polytechnic University Human Subjects Ethics Sub-committee. Twenty healthy adult male Hong Kong residents were recruited. All were nonsmokers and none was on any medication. They were fully informed of the methods and risks before consent was obtained. The twenty subjects were divided randomly into two groups (with and without UV blocking fabric protection); each group contained ten male subjects. The physiological data of the volunteers in each group is summarized in Table 7-2.

Table 7-2 Physical characteristics of the subjects (Mean±STD)

	Protected group	**Unprotected group**
Weight (kg)	60.44±14.73	64.43±11.53
Age	22.00±2.71	22.60±1.90
Height (cm)	174.00±6.53	171.60±5.13

All subjects were asked to maintain their regular routines from one week before to the end of the experimental period, to avoid smoking, alcohol, vigorous exercise, late nights, and certain foods, such as coffee, tea, bananas, chocolate, cocoa, citrus fruits, and vanilla. They were asked not to use anti-UV cream on their bodies before the experiment and not to expose themselves to the sun six weeks before the experiment.

The experiment was carried out on 5th January 2006 in Hong Kong. The weather conditions for the experimental period were recorded as: temperature 33.0.±2.64ºC, wind speed (1.13±0.56m/s), and average relative humidity (81.8±5.9%) (Observatory

2006). The intensity of UV radiation was 22.79±4.35 W/m^2 for UVA and 0.72±0.14 W/m^2 for UVB during the exposure period (details are shown in Fig. 7-2).

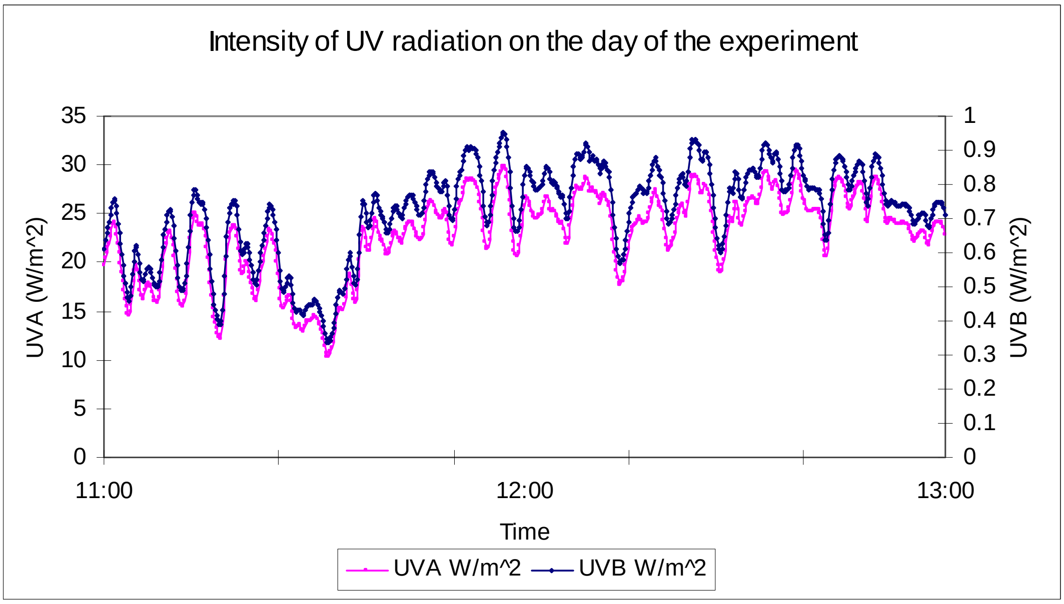


Figure 7-2 Intensity of UV radiation on the day of the experiment

In the group wearing the protective fabric, subjects used a piece of UV blocking fabric to cover their backs. In the unprotected group, subjects wore pajamas and fully exposed their backs. All subjects stayed in a climate controlled chamber with the temperature set at room temperature, 20±1°C, and with a relative humidity of 50±5% for 3 hours. After answering questionnaires I and II (Buysee D. J et al. 1989), samples were taken from the central area of the subjects' spinal columns, from T4 to T6, to measure their melanin content and erythem. A total of 10 ml fasting blood samples were collected for further immunophenotyping, and total antioxidant capacity and white blood count measurement. These were analyzed as soon as possible after collection. The protocol is illustrated in Fig. 7-3.

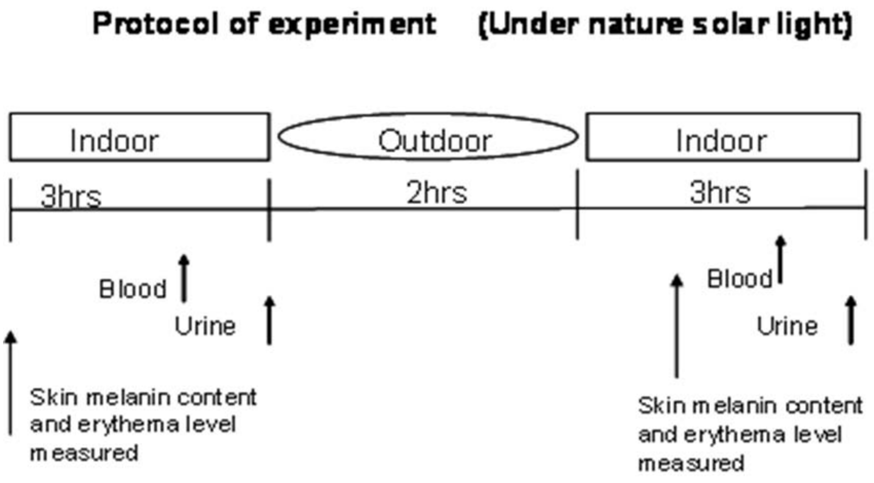


Figure 7-3 Protocol of the solar exposure experiment

7.2.5 Statistical analysis

Skin physiology, hormone, and immunophenotyping data are presented as mean ± SD. The statistical analysis were performed using a paired T-test in SPSS 12 to compare the differences between the data from before and after exposure to the sun and between the with/without UV blocking fabric protection groups. T-test was applied to compare the difference between the with/without UV blocking fabric protection groups after exposure. Subjective fatigue symptoms data are presented as medium (minimum-maximum). Mann-Whitney U test was conducted to confirmed differences in subjective fatigue symptoms. Differences were considered significant at $p < 0.05$.

7.3 Results

7.3.1 Cutaneous responses

TEWL

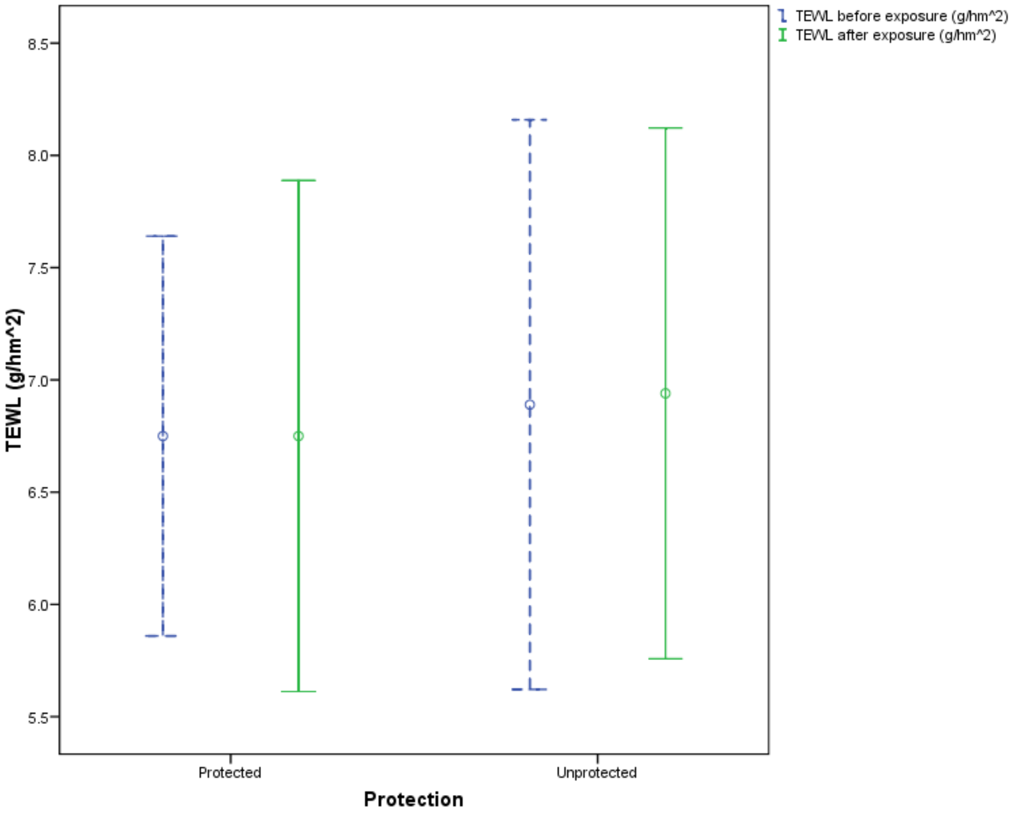


Figure 7-4 TEWL responses in protected and unprotected groups

Regarding the TEWL response, there was no significant difference between the protected and unprotected groups after solar exposure (Fig. 7-4). Solar exposure seems not to induce change of TEWL both in the protected and unprotected groups (Table 7-3).

Table 7-3 TEWL response to solar exposure

Cutaneous response after solar exposure				
	Protected group	**Unprotected group**	**Significance of difference**	
			t	**Sig. (2-tailed)**
TEWL(g/hm2)	6.75±1.59	6.94±1.65	-0.26	0.80

Cutaneous response in unprotected group

	Before solar exposure	After solar expsore	Significance of difference	
			t	Sig. (2-tailed)
TEWL(g/hm2)	6.89±1.77	6.94±1.65	-0.08	0.94

Cutaneous response in protected group

	Before solar exposure	After solar expsore	Significance of difference	
			t	Sig. (2-tailed)
TEWL(g/hm2)	6.75±1.24	6.75±1.59	0.00	1.00

SCWC

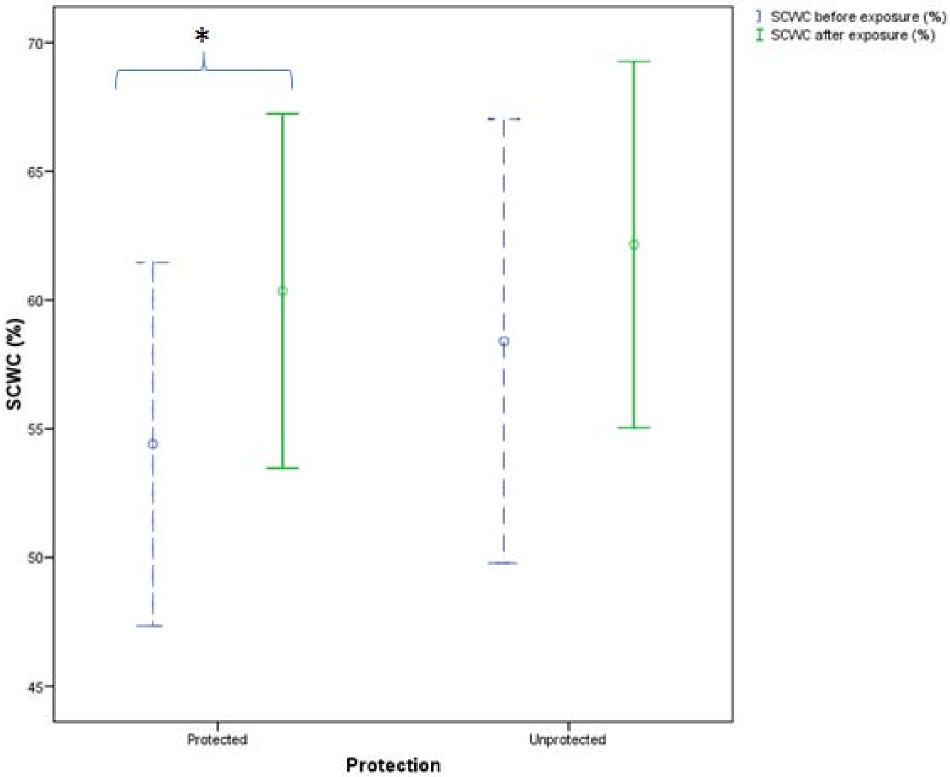


Figure 7-5 SCWC responses in protected and unprotected groups

Table 7-4 SCWC responses to solar exposure

Cutaneous response after solar exposure

	Protected group	Unprotected group	Significance of difference	
			t	Sig. (2-tailed)
SCWC(%)	60.36±9.63	62.16±9.94	-0.41	0.68

Cutaneous response in unprotected group

	Before solar exposure	After solar expsore	Significance of difference	
			t	Sig. (2-tailed)
SCWC(%)	58.40±12.06	62.16±9.93	-1.20	0.26

Cutaneous response in protected group

	Before solar exposure	After solar expsore	Significance of difference	
			t	Sig. (2-tailed)
SCWC(%)	54.40±9.87	60.36±9.63	-3.02	0.01**

SCWC responding to the solar exposure showed that there was no significant difference between the protected and unprotected groups after solar exposure (Fig. 7-5). In unprotected groups, SCWC did not change significantly after solar exposure, while SCWC in protected groups increased significantly ($t=-3.02$, $p<0.01$) after solar exposure (Table 7-4).

- Melanin content

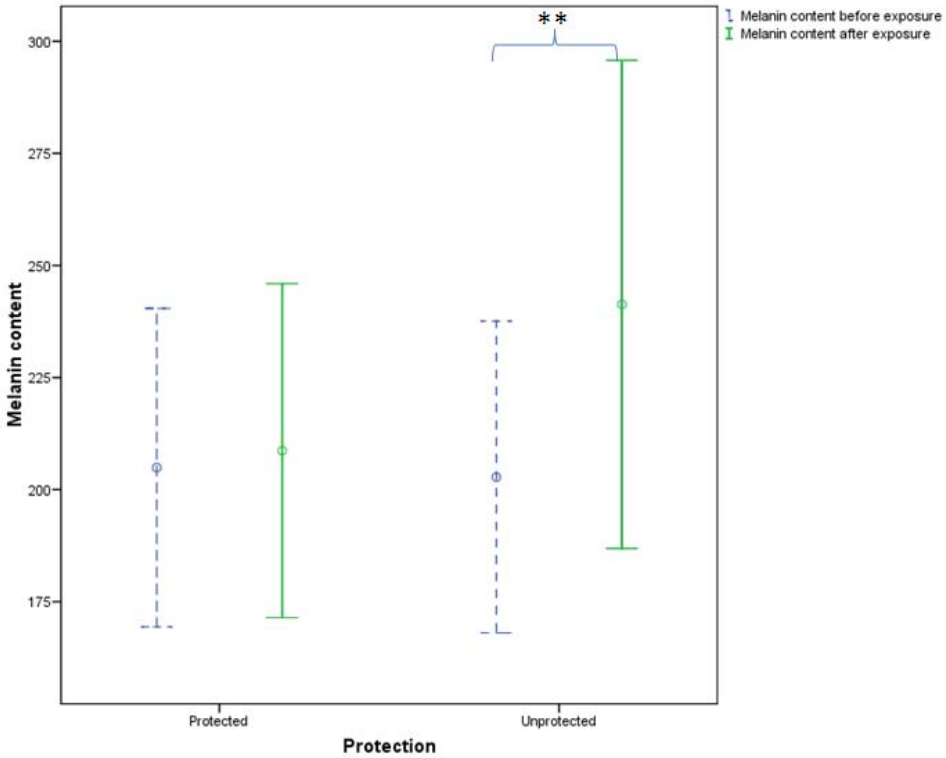


Figure 7-6 Melanin content responses in protected and unprotected groups

The response of melanin content in protected and unprotected groups is illustrated in Fig. 7-6. There is no significant difference between protected and unprotected groups. However, melanin content in unprotected groups significantly increased ($t=-3.42$, $p<0.01$), while no significant effect was found in the protected group (Table 7-5).

Table 7-5 Melanin content responses to solar exposure

Cutaneous response after solar exposure				
	Protected group	**Unprotected group**	**Significance of difference**	
			t	**Sig. (2-tailed)**
Melanin content	208.69±52.08	241.33±76.08	-1.12	0.28

Cutaneous response in unprotected group

	Before solar exposure	After solar expsore	Significance of difference	
			t	**Sig. (2-tailed)**
Melanin content	202.80±48.59	241.33±24.06	-3.42	0.01**

Cutaneous response in protected group

	Before solar exposure	After solar expsore	Significance of difference	
			t	**Sig. (2-tailed)**
Melanin content	204.91±49.65	208.69±52.08	-0.44	0.67

- Erythem responses to solar exposure

Erythem response to solar exposure in the protected and unprotected groups is illustrated in Fig. 7-7. Solar exposure significantly increases erythem level in unprotected group ($t=-3.98$, $p<0.000$), but does not induce significant change in protected group (Table 7-6).

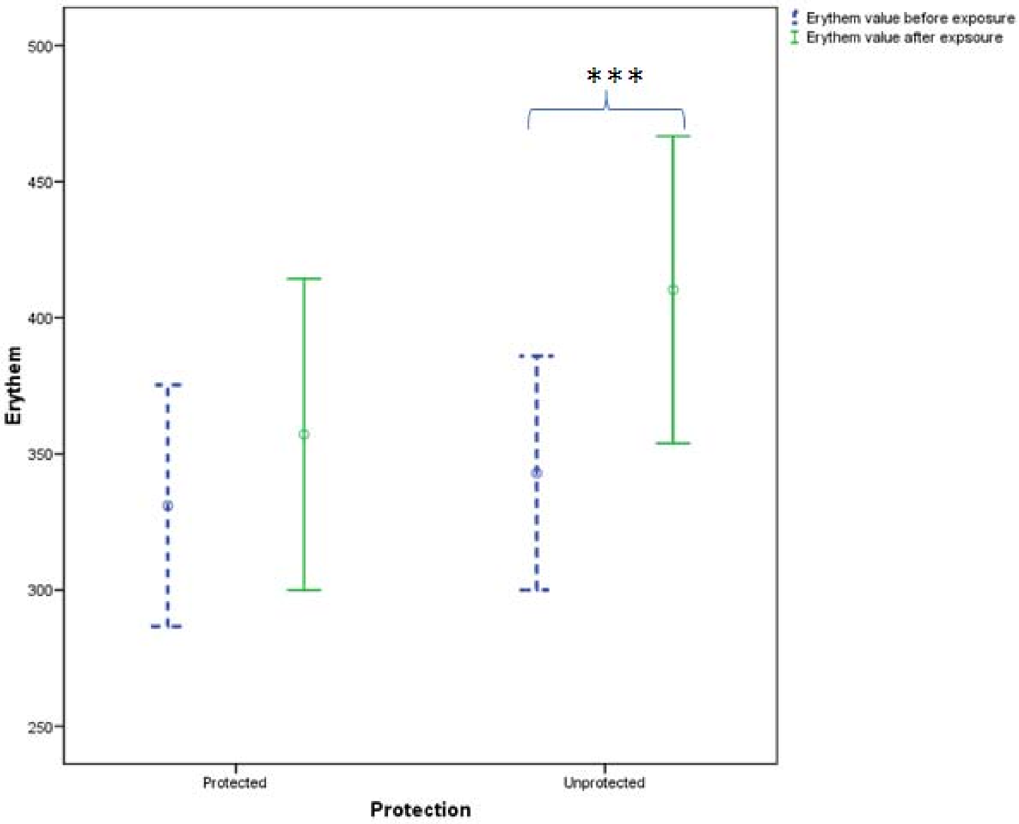


Figure 7-7 Enythem response in protected and unprotected groups

Table 7-6 Erythem responses to solar exposure

Cutaneous response after solar exposure				
	Protected group	**Unprotected group**	**Significance of difference**	
			t	**Sig. (2-tailed)**
Erythem value	357.16±79.92	410.33±78.80	-1.50	0.15

Cutaneous response in unprotected group				
	Before solar exposure	**After solar expsore**	**Significance of difference**	
			t	**Sig. (2-tailed)**
Erythem value	342.98±60.03	410.33±78.80	-3.98	0.00***

Cutaneous response in protected group				
	Before solar exposure	**After solar expsore**	**Significance of difference**	
			t	**Sig. (2-tailed)**
Erythem value	331.00±61.987	357.16±79.92	-1.78	0.11

7.3.2 Catecholamines

The urinary free catecholamines were measured from urine. The total amount of norepinephrine (NE), epinephrine (E), dopamine (Dopa), and catecholamines is presented in Table 7-7. There is no significant difference between protected and unprotected groups (Fig. 7-8).

Table 7-7 Urinary free catecholamines in the protected and unprotected groups

Difference of catecholamines after solar exposure				
	Protected group	**Unprotected group**	**Significance of difference**	
	Mean±STD	**Mean±STD**	**t**	**Sig. (2-tailed)**
NE (nmol)	13.14±4.79	9.99±5.58	1.21	0.24
E (nmol)	3.03±1.80	3.27±2.00	-0.25	0.81
Dopa (nmol)	126.94±25.45	100.13±47.75	1.35	0.20
Catecholamines (nmol)	143.89±31.83	112.38±56.74	1.31	0.21

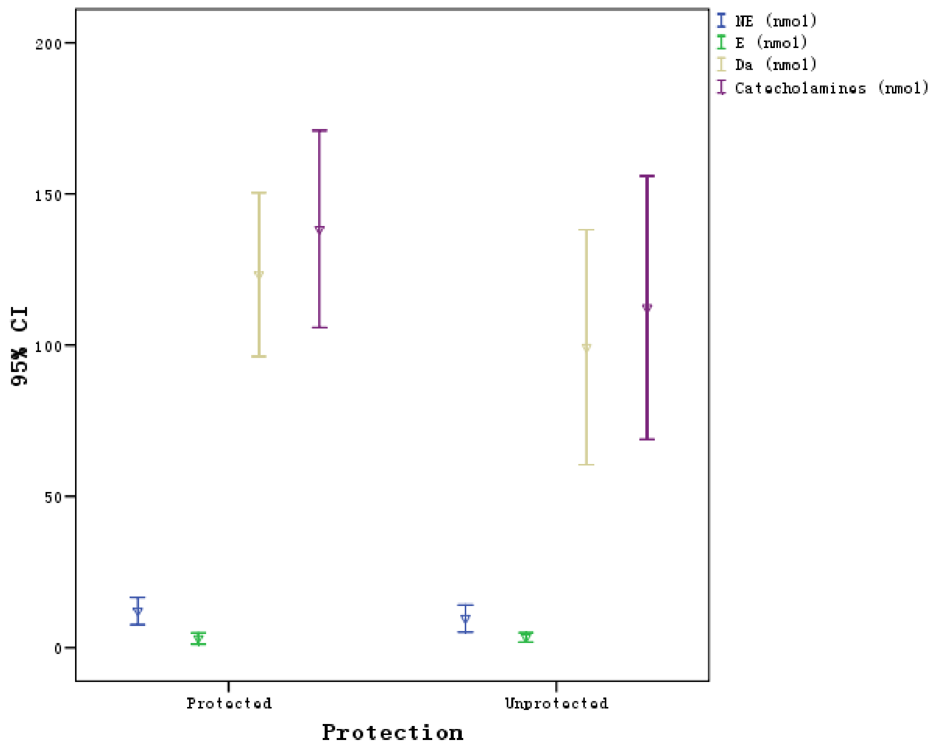


Figure 7-8 Urinary free catecholamines after solar exposure

7.3.3 Fatigue symptoms

There was no significant difference in terms of Fatigue I (drowsiness and dullness), Fatigue II (difficulty in concentration) and Fatigue III (projection of disintegration). These results indicated that, with or without the UV blocking fabric protection, there was no influence on the fatigue symptoms of subjects with two hours of solar exposure (Table 7-8).

Table 7-8 Difference of fatigue symptoms in groups with/without UV blocking fabric protection

		Protected group Median (range)	Unprotected group Median (range)	Mann-Whitney U test (p value)
Fatigue I	Before exposure	3 (2-10)	3 (2-8)	0.055
(drowsiness and dullness)	After exposure	3 (2-7)	3 (2-7)	0.306
Fatigue II	Before exposure	3 (2-10)	3 (2-9)	0.789
(difficulty in concentration)	After exposure	2 (2-7)	3 (2-7)	0.509
Fatigue III	Beofre expousre	2 (2-9)	3 (2-7)	0.966
(projection of disintegration)	After expousre	2 (2-8)	2 (2-7)	0.512

7.4 Discussion and conclusions

Stratum corneum hydration characterized by circadian rhythmicity (Yosipovitch et al. 1998) is higher in the afternoon than in the morning. The protected group in this study followed this pattern; however, the SCWC in the group without UV blocking fabric protection did not increase in the afternoon. This indicates that UV may have interfered with the circadian rhythm of the epidermis in the group without UV blocking fabric protection.

Previous studies have shown that UVA radiation (0.6 $mWcm^{-2}$) could induce apoptosis in human skin fibroblasts even at low dose of UVA. (Wang et al. 2003). A suberythemal dose (0.5 minimal erythema dose) of UVB irradiation can be responsible for the observed abnormal intercellular structure and barrier disruption in stratum corneum (Meguro et al. 1999), and increase TEWL (Shao et al. 2006). Water content, water-holding capacity and hygroscopicity decreased after UVB irradiation; the decrease being roughly dependent on the UVB dose (Miyauchi et al. 1993). The hydration level and levels of natural moisturizing factors (free amino acids and pyrrolidone) in the stratum corneum decreased by mid-wavelength UV (UVB) irradiation in guinea pig skin; the decrease was proportional to the intensity of UVB irradiation (Tsuchiya et al. 1988). This study shows that there are no significant differences between SCWC and TEWL before and after solar exposure in the protected group. This demonstrates the effects from the use of UV blocking fabric, as it can block UV radiation, and protects normal physiology function in the epidermal. The protection function from the UV blocking fabric can also perform and inhibit melanin content and increase erythem when solar exposure occurs for the protected group.

Studies have widely shown that UV radiation induces immunological, epidermal responses. However, this study did not demonstrate any effects of UV and the effects of UV blocking fabric protection on responses in terms of stress (catecholamines) and fatigue symptoms response. One of reasons for this might be that the subjects in this study live at low latitude. Previous studies have shown that certain thresholds exist in physiological response to UV radiation (Luger et al. 1990; Boelsma et al. 2001). The fact that the inhabitants of Hong Kong not only live at a low latitude but also face with high UV radiation intensity, may cause them to have a higher UV radiation tolerance.

From this chapter, hypothesis VII has been verified as:

- The UV blocking property of clothing reduces the acute effects of solar exposure, inhibits melanin content and erythem level and circadian rhythmicity disorder, and increases stratum corneum hydration under UV radiation.

Chapter 8 Conclusions and Further Work

8.1 Conclusions

Based on systematic review of the fundamental knowledge framework, knowledge gaps on effects of clothing on skin physiology were identified. The purpose of this research was to fill the knowledge gaps and establish a systematic framework to study the effects of clothing on skin physiology.

This purpose has been achieved by successfully dealing with the six objectives identified, through carrying out systematically designed wear trials in mildly cold and hot conditions, as well as under solar exposure to investigate the effects of clothing on skin physiology in different conditions.

The objectives were completed and results are summarized as follows:

1) To develop a framework of effects of clothing on skin physiology from the perspective of physics, biochemistry, physiology, neuropsychology, and immunology;

This objective has been achieved as presented in Chapter 2, 3, 4, 5, 6 and 7. In Chapter 2, based on systematic literature review, a theoretical framework was proposed to map potential interaction of clothing with skin physiology from physical, physical-physiological, physical-neuropsychological, and physical-physiological/immunological as well as neuropsychological-physiological effects. Seven hypotheses have been proposed to suggest the likelihood of predicting possible interactions among clothing and skin physiology. This theoretical framework and hypotheses have been further verified in Chapter 3, 4, 5, 6 and 7, which are briefly described in the following paragraphs.

2) To clarify the effects of clothing material on skin physiology in daily wear in mildly cold condition without sweating;

This objective has been achieved in Chapter 3. A parallel, cross-over, blinded wear trial was designed to investigate whether polyester and/or cotton fabric influence skin physiology during daily wear in mildly cold condition. The result indicates that SCWC level is significantly higher when wearing cotton pajama than polyester pajama; Influence of pajama material on subjective *coldness* sensation and stress level also have been noted; cotton fabric, with higher moisture sorption capacity and lower thermal diffusivity, has a positive effect on SCWC; while *coldness* sensation has a negative effect on SCWC.

3) To identify effects of moisture/liquid water transports properties of fabric on the skin physiology in daily wear in mildly cold condition without sweating;

This objective has been achieved in Chapter 4. A parallel, blinded design wear trial in mildly cold condition has been conducted to investigate moisture/liquid water transports properties on skin physiological status, such as SCWC, TEWL, sebum, and skin surface acidity. The result suggests that hygroscopicity of fabric significantly influence SCWC and TEWL in mildly cold conditions during the three-weeks of wear trial; hygroscopicity of fabric tends to influence skin surface acidity; and no significant effects from hygroscopicity of fabric on sebum has been noted. Additionally, no significantly effects from hydrophilicity of fabric on skin physiology has been found from this wear trial.

4) To explore the mechanisms of effects of clothing properties on skin physiological status in daily wear in mildly cold condition without sweating;

This objective has been dealt with in Chapter 5 applying first hand data from two systematically designed wear trials carried out in mildly cold conditions (Chapter 3 and 4), statistical methods, factor analysis and Hierarchical Linear Regression, were used to obtain strong predictors of skin physiological parameters such as SCWC, TEWL, sebum, and skin surface acidity. A framework has been generated, which describes clothing-wearer interactions in terms of sensory response, as well as skin physiological and neuropsychological response in mildly cold condition (Fig. 5-1).

Hydroscopic fabric significantly increases SCWC and TEWL and decreases sebum in mildly cold condition. Fabric transport capability significantly reduces skin surface acidity due to the fact that it promotes heat release thus reducing heat accumulation surrounding the skin. Fabric transport capability enhances sensation of *overall comfort* and reduces stress; while fabric shearing resistance reduces *overall comfort* while increasing stress level. Fabric compressibility and OMMC enhance *overall comfort* sensation. Sensations of *overall comfort* significantly increase SCWC and TEWL; It also was noted that stress level seems to increase sebum.

5) To study the effects of clothing on skin physiology in hot condition, and explore the mechanisms;

This objective has been achieved in Chapter 6. From a systematically designed cross-over blinded wear trial conducted in hot environment, effects of clothing on skin physiology under different activities have been investigated. It was found that runing in hot weather increases various factors namely: (a) heat accumulation in human body, (b) core temperature, (c) skin evaporation and stratum corneum water content, and (d) microclimate humidity between skin and fabric. Properties of fabric influence the human heat regulation via their impact on heat release, then, affect microclimate humidity, skin evaporation, stratum corneum water content, and skin and core temperature.

Hygroscipicity of fabric significantly increases SCWC and skin evaporation. Hydroscopic and hydrophilic properties of fabric significantly reduce skin-clothing microclimate humidity, and decrease human body core and skin temperatures. Fabric with stronger transport capability significantly reduces core and skin temperature due to the fact that it promotes heat release from human body to external environment. Fabric with higher shearing resistance increases skin temperature. (Fig. 6-18 and 6-19) A framework is thus generated, describing clothing-wearer interactions in terms of fabrics' physical properties, sensory, skin physiological, neuropsychological and thermal physiological response in hot conditions.

6) To study the effects of UV blocking fabric on skin physiology under solar exposure.

The achievement of this objective has been achieved in Chapter 7. From a parallel designed wear trial carried out with solar exposure, cutaneous, stress and fatigue symptom response with or without UV blocking fabric protection has been investigated. It has been found that UV blocking fabric reduces the acute effects of solar exposure, inhibits melanin content as wellp as erythem level and circadian rhythmicity disorder, while increasing stratum corneum hydration under UV radiation.

It also has been found that the inhabitants of Hong Kong have a higher UV radiation tolerance.

From this study, clothing-wearer interactions under mildly cold and hot conditions as well as under solar exposure have been investigated. Two frameworks have been presented to describe fabric physical properties, skin physiology, thermal physiology, and neuropsychology. The outcome of this research contributes significantly to the knowledge of the skin physiological health, comfort and safety of the wearer in our daily life under different environmental conditions.

8.2 Further work

The objectives of this research have been achieved, which have established an appropriate foundation for further investigation.

On the basis of the research outputs, skin physiology responses to fabric worn in mildly cold condition, hot environment, and under solar exposure can be predicted from fabric physical properties by using the framework and statistical modeling obtained from this study.

Limited by the research resources, all results obtained were based on a small population. The prediction models need to be validated with large populations with consideration of peoples' race, and age group, so that we extend the typical population since in this research, young Chinese have been selected as subject.

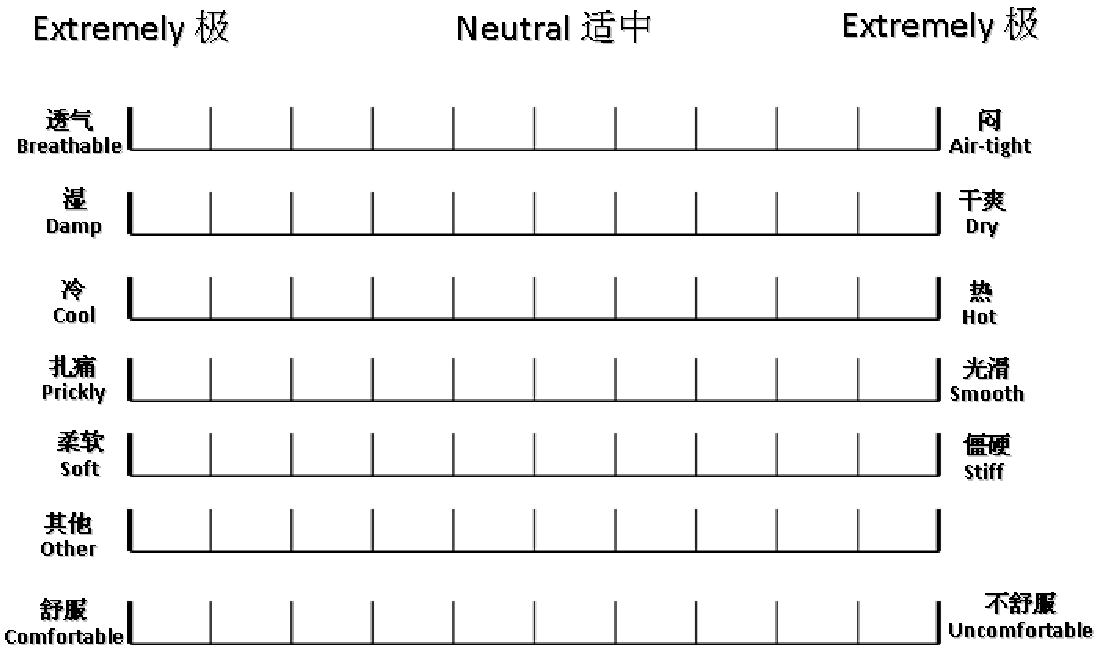
Sebum (cholesterol and free fatty acids) responses to fabric has been studied in this investigation, while, ceramides, though essential for skin physiology, have not been systematically studied. The skin lipids sample has been collected during the wear trial, but analysis of ceramids has not been conducted due to the limitation of biochemical analysis technology and facility. After analysis of the ceramids, more comprehensive results should be obtained to understand skin physiology responses to clothing in the future.

It is hoped that further research will provide textile scientists with a more solid foundation, indeed the initial work towards that foundation has been undertaken as delineated above.

Appendix

Appendix I

Subjective sensation questionnaire



Appendix II
Pittsburgh Sleep Quality Index (PSQI)

Pittsburgh Sleep Quality Index (PSQI)

Instructions: *The following questions relate to your usual sleep habits during the past month only. Your answers should indicate the most accurate reply for the majority of days and nights in the past month. Please answer all questions.*

During the past month,

1. When have you usually gone to bed? ___________
2. How long (in minutes) has it taken you to fall asleep each night? ___________
3. When have you usually gotten up in the morning? ___________
4. How many hours of actual sleep did you get that night? (This may be different than the number of hours you spend in bed) ___________

5. During the past month, how often have you had trouble sleeping because you…	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times a week (3)
a. Cannot get to sleep within 30 minutes				
b. Wake up in the middle of the night or early morning				
c. Have to get up to use the bathroom				
d. Cannot breathe comfortably				
e. Cough or snore loudly				
f. Feel too cold				
g. Feel too hot				
h. Have bad dreams				
i. Have pain				
j. Other reason(s), please describe, including how often you have had trouble sleeping because of this reason(s):				
6. During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?				
7. During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?				
8. During the past month, how much of a problem has it been for you to keep up enthusiasm to get things done?				
	Very good (0)	Fairly good (1)	Fairly bad (2)	Very bad (3)
9. During the past month, how would you rate your sleep quality overall?				

Component 1 #9 Score C1 ______
Component 2 #2 Score (≤ 15min (0), 16-30 min (1), 31-60 min (2), >60 min (3)) **+** #5a Score (if sum is equal 0=0; 1-2=1; 3-4=2; 5-6=3) C2 ______
Component 3 #4 Score (>7(0), 6-7(1), 5-6(2), <5 (3) C3 ______
Component 4 (total # of hours asleep)/(total # of hours in bed) **x** 100
>85%=0, 75%-84%=1, 65%-74%=2, <65%=3 C4 ______
Component 5 # sum of scores 5b to 5j (0=0; 1-9=1; 10-18=2; 19-27=3) C5 ______
Component 6 #6 Score C6 ______
Component 7 #7 score **+** #8 score (0=0; 1-2=1; 3-4=2; 5-6=3) C7 ______

Add the seven component scores together ______ **Global PSQI Score** ______

Adapted from: Buysse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R., & Kupfer, D.J. (1989). The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. Psychiatric Research, 28(2), 193-213, with permission from Elsevier Science.

Appendix III

Mechanical properties of fabrics applied in Chapter 3

	Fabric	Hydrophilic cotton pajama (Mean±STD)	Hydrophilic polyester pajama (Mean±STD)	
Tensile	LT	0.34±0.02	0.30±0.03	***
	WT(N/m)	1.26±0.05	1.60±0.11	***
	RT(%)	42.52±4.06	40.60±2.02	***
	EM(%)	15.08±0.55	20.85±2.53	***
Shear	G(N/m/deg)	0.99±0.02	0.73±0.04	***
	2HG(N/m)	2.93±0.20	2.70±0.13	***
	2HG5(N/m)	3.35±0.33	2.89±0.28	***
Bending	B(x 10-4 Nm/m)	0.02±0.00	0.02±0.00	***
	2HB(x 10-2 N/m)	0.02±0.00	0.028±0.00	***
Lateral	LC	0.36±0.01	0.39±0.03	***
compression	WC(N.m/m2)	0.36±0.01	0.39±0.03	***
	RC(%)	48.02±3.78	51.48±0.44	***
Surface	MIU	0.22±0.00	0.28±0.00	***
characteristics	MMD	0.01±0.00	0.04±0.00	***
	SMD(μm)	3.53±0.18	5.88±0.50	***

Appendix IV
Mechanical properties of clothing fabric applied in Chapter 4

	Fabric	Hydrophilic cotton pajama (Mean±STD)	Hydrophobic cotton pajama (Mean±STD)	Hydrophilic polyester pajama (Mean±STD)	Hydrophobic polyester pajama (Mean±STD)	
Tensile	LT	0.81±0.05	0.82±0.02	0.42±0.20	0.45±0.09	***
	WT(N/m)	3.97±1.73	6.58±2.43	1.42±0.55	1.71±0.54	***
	RT(%)	55.02±1.45	53.17±3.37	41.92±1.35	22.18±1.91	***
	EM(%)	20.27±9.03	32.39±11.53	14.01±3.48	15.63±4.41	***
Shear	G(N/m/deg)	0.75±0.01	0.59±0.05	0.72±0.05	0.64±0.02	***
	2HG(N/m)	3.22±0.43	2.42±0.07	2.81±0.43	2.36±0.28	***
	2HG5(N/m)	3.26±0.38	2.48±0.06	2.98±0.38	2.47±0.22	***
Bending	B(x 10-4 Nm/m)	0.06±0.03	0.06±0.03	0.02±0.01	0.02±0.01	***
	2HB(x 10-2 N/m)	0.08±0.04	0.08±0.03	0.03±0.01	0.03±0.01	***
Lateral compression	LC	0.35±0.01	0.32±0.01	0.34±0.01	0.36±0.01	***
	WC(N.m/m2)	0.61±0.00	0.43±0.03	0.47±0.02	0.66±0.02	***
	RC(%)	32.18±0.45	34.53±3.55	44.67±0.85	43.70±0.86	***
Surface characteristics	MIU	0.25±0.01	0.31±0.03	0.26±0.01	0.25±0.02	***
	MMD	0.03±0.02	0.04±0.03	0.03±0.02	0.03±0.02	***
	SMD(μm)	4.21±2.56	7.56±4.51	6.76±5.78	10.52±7.14	***

Appendix V

Physical properties of clothing fabric applied in Chapter 6

	Water vapor permeability (g/m^2/24h)			Moisture regain (%)			Air Resistance (Kpa*s/m)		
Fabric	Mean	±	STD	Mean	±	STD	Mean	±	STD
Hydrophilic PE	456.44	±	24.20	1.18	±	0.06	0.09	±	0.01
Hydrophobic CT	424.71	±	29.74	6.78	±	0.06	0.34	±	0.02
Hydrophobic PE	423.65	±	29.55	1.57	±	0.09	0.10	±	0.01
Hydrophilic CT	400.40	±	17.96	6.73	±	0.25	0.37	±	0.02

	Thermal conductivity (W/ ˚C.m)			Warmth keeping ratio (%)			Contact angle (˚)		
Fabric	Mean	±	STD	Mean	±	STD	Mean	±	STD
Hydrophilic PE	0.05	±	0.00	27.35	±	5.75	0.00	±	0.00
Hydrophobic CT	0.06	±	0.00	11.82	±	1.97	95.00	±	0.00
Hydrophobic PE	0.05	±	0.00	31.62	±	7.41	95.00	±	0.00
Hydrophilic CT	0.05	±	0.00	15.53	±	6.00	0.00	±	0.00

(PE=polyester, CT=cotton)

Appendix IV

Comparing of air resistance and thermal conductivity in dry and wet

	Air Resistance (Kpa*s/m) (Dry)			Air Resistance (Kpa*s/m) (wet)			**Water content (%) (Wet)**		
Fabric	Mean	±	STD	Mean	±	STD	Mean	±	STD
Hydrophilic PE	0.09	±	0.01	0.09	±	0.01	247.72	±	8.85
Hydrophobic CT	0.34	±	0.02	0.33	±	0.01	52.02	±	2.00
Hydrophobic PE	0.10	±	0.01	0.09	±	0.02	21.63	±	1.09
Hydrophilic CT	0.37	±	0.02	10.00	±	0.00	163.29	±	10.32

	Thermal conductivity (W/ ˚C.m) (Dry)			Thermal conductivity (W/ ˚C.m) (Wet)		
Fabric	Mean	±	STD	Mean	±	STD
Hydrophilic PE	0.05	±	0.00	0.13	±	0.01
Hydrophobic CT	0.06	±	0.00	0.10	±	0.01
Hydrophobic PE	0.05	±	0.00	0.07	±	0.01
Hydrophilic CT	0.05	±	0.00	0.14	±	0.01

(PE=polyester, CT=cotton)

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