提昇保溫舒適度的技術與科技分析

Analysis of techniques and technologies used to improve thermal comfort

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摘要

對服裝設計師而言，設計用於寒冷天氣，且具有排汗功能的服裝是一大挑戰。用於寒天的運動服飾，其理想的狀態是能將汗水導至衣服表面後，蒸發。設計師除了瞭解材質的特性外，也必須意識到其他能增進保暖舒適的技術和科技。例如，層次性的著裝技術已被倡導多年。此外，美國軍方已研發出電熱系統及管線系統的短程液態冷卻/暖化服飾 (SLCWG) 的科技。本研究主要是探討人體對寒冷環境的反應及這些技術和科技的運作。這個研究不但提供有關保暖舒適度的訊息，且能幫助設計師研發出具創意性的產品。

關鍵詞：保暖舒適，層次性，管線，服裝科技。

ABSTRACT

Clothing designers are challenged by the need to design garments that can handle cold weather and can still get rid of sweat. The role of ideal clothing used for exercise in the cold is to pass sweat to the clothing surface where vapor can evaporate. In addition to understanding material properties, designers have to be aware of techniques and technologies that can be applied to improve thermal comfort. For instance, the clothing layering system is a popular technique that has been promoted for years. The electrically heated system and the tubing system of Shortened Liquid Cooling/Warming Garments (SLCWG) are technologies that have been developed by the U. S. military. The purpose of this study is to analyze how the human body reacts to a cold environment and how these techniques and technologies function. The content analysis provides designers with information related to thermal comfort and helps designers come up with innovative products.

Keywords: thermal comfort, layering, tubing, clothing technology

1. Introduction

Apparel products designed for use in cold environments have increased in the past 10 years. Although the garments are considerably planned for protecting human bodies from the cold, clothing is regarded as a barrier to thermal comfort during exercise. During exercise in a cold environment, the metabolism of human bodies releases excessive heat by sweating, which generates thermal discomfort and overcooling, especially when the material cannot transfer sweat from skin to a clothing surface. The major challenge for designers of protective clothing is to resolve the problem of sweat accumulation. The technique of clothing layering system has been promoted to improve thermal comfort. The technologies of electrically heated system and tubing system sewn in Shortened and Liquid Cooling/Warming Garments (SLCWG) are experimented by the military to eliminate sweating problems. Apparel designers have to be aware of these new techniques and technologies that can be

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applied to design protective products, such as gloves or mittens, for use in a cold environment. The purpose of this study is to analyze how the human body responds to the cold and how the techniques and technologies function to protect the human body from the cold.

2 . Reaction of the human body to a cold environment

The human body is capable of maintaining heat balance, the amount of heat produced by the human body equal to the amount of heat loss, in a cold environment. Radiation, conduction, and convection are additional resources that help the human body keep heat balance. However, the metabolism that releases excessive heat by sweating is an inefficient way. If the moisture is not completely evaporated from the clothing, the body becomes overcooled.

2.1 Heat balance

Like other warm-blooded mammals, human beings are able to maintain heat balance. The human body with a thermal-regulated system normally keeps temperature around 37°C (McCullough & Rohles, 1983; Watkins, 1995; Havenith, 1999; Davenport, 2002). The human body releases excessive heat before the temperature becomes too high. Excessive heat is carried by blood vessels from the internal body tissues to the skin surface, and then it is dissipated to the environment. Blood vessels are the vehicle to operate heat dissipation, as well as heat generation. When the environment temperature decreases, blood vessels are constricted and the speed of blood flow becomes slow. The slow blood flow restricts heat transferred from the body core to skin surface. Thus, internal body temperature is stable, even though the skin temperature is low. Particularly, the skin temperatures of fingers and toes drop dramatically because their locations are at the end of the blood circulatory network (McCullough & Rohles, 1983). Furthermore, the head loses great amount of heat in cold because blood circulation close to the head and face skins does not have the effect of vessel constriction. The protection of the head, face, and ears is as important as the body torso in winter (Gonzalez, 1995; Watkins, 1995).

2.2 Mechanisms that help keep heat balance

Human beings are capable of maintaining heat balance within certain limitations. In addition to the metabolism of the human body, heat balance relies on the mechanisms of conduction, convection, and radiation (Gavin, 2003). One mechanism that facilitates heat conservation is the metabolism of the human body. For example, food oxidation by the muscles is a metabolic function to provide heat in terms of fat deposits. The metabolic rate of an individual is determined by activity or exercise, age, gender, race, disease, and other factors (Watkins, 1995; Havenith, 1999). Young children require greater heat production in maintaining heat balance compared to adults. Women exhibit lower sweat rates, higher heart rates, and higher core temperatures compared with men while doing light or moderate exercise in the cold environment. Meanwhile, the skin temperatures of women cool quicker than those of men who appear to have similar weights. Women’s skin temperatures on the trunk and legs are lower than those of men (Koscheyev, Coca, Leon, and Dancisak, 2002). Along with the metabolism of the human body, radiation, conduction, and convection are other mechanisms to help absorb heat from the environment. For instance, standing in front of a fire helps the human body to absorb heat through radiation, a heat pad provides a conductive way for the body to obtain heat, and sitting in a sauna enables heat absorption through convection (Watkins, 1995).

However, the metabolism of the human body, radiation, conduction, and convection contribute to heat loss, as well (McCullough & Rohles, 1983; Havenith, 1999; Davenport, 2002). Evaporation and respiration are the metabolic functions of the human body that affect heat loss. The human body releases excessive heat by sweating, and moisture is evaporated from the body. Whereas evaporation dissipates heat through the skin, respiration releases heat by breathing cool and dry air. If the air temperature is lower than that of lung's surface, heat is lost through respiration (Havenith, 1999; Gavin, 2003). Radiation is another example of heat loss. The warm body allows heat quickly to dissipate from the skin surface to the cold air. When cold air encompasses the human body, body heat is transferred from the skin to the cold and still air. Heat transfer is stopped only if there is no difference between the skin and environment temperatures. The body in touch with the surface of cold items experiences heat loss. The warm body and cold object exchange heat. Heat flows from the body into object until both are at an equal temperature. Furthermore, heat loss occurs through convection as heat exchanges between the body and a moving medium such as wind. The interaction between body and wind movements causes heat loss (Watkins, 1995; Davenport, 2002; Gavin, 2003).

Among these mechanisms, evaporation is the metabolism of the human body that maintains heat balance during exercise in a cold environment. The body begins sweating to dissipate excessive heat. However, sweating is an inefficient way to achieve heat loss. If the moisture cannot completely be evaporated from the clothing, part of the vapor stays and continues to slowly dissipate (McCullough & Rohles, 1983; Giesbrecht, 2003). When moisture stays on the skin and slow evaporation happens, the human body becomes uncomfortable. Moreover, for those people who participate in intensively physical activities in a cold environment whether for exercise or for their work, the clothing insulation is high and leads to excessive sweating. When they temporarily leave the cold places or the exercise rate decreases, overcooling or illness arises due to the wet clothing. Thus, clothing is considered a barrier to evaporation if the material does not allow sweat to be evaporated quickly. To avoid thermal discomfort and overcooling, designing protective clothing has to aim at reducing sweat accumulation (Havenith, 1999; Gavin, 2003).

3 . Techniques and technologies used to improve thermal comfort

The major purpose of clothing is to protect bodies from the cold environment. During exercise in the cold, heat produced by metabolism is turned into water vapor that slowly evaporates from the skin. The ideal clothing transfers the vapor to the clothing surface and increase comfort level. Designers have to understand the material properties of permeability and moisture transfer as well as to be aware of the existence of techniques and technologies that can be applied to improve thermal comfort.

3.1 Thermal comfort

Clothing helps regulate thermal conditions and increases the comfort level (McIntyre & Griffiths, 1975; Gonzalez, 1995). Clothing comfort is associated with the interaction of people, environment, and properties of materials. A person's thermal comfort depends on factors including the environment temperature, air velocity, the relative humidity, metabolism of the human body, and moisture transfer through fabrics. Other factors including color, fashion, and physical and psychological states also influence the perception of comfort (Weder, 1996). Designers have to understand the material properties of permeability and moisture transfer, and they have to be aware of the existence of techniques and technologies that can be applied to improve thermal comfort.

3.2 Permeability and moisture transfer

The sweating problem is the major challenge for designing textiles and garments used for the cold environment. The ideal clothing allows vapor to pass to the clothing surface where moisture can be evaporated. Otherwise, moisture that remains in the fibers decreases thermal insulation because heat continues to lose through wet clothing (Giesbrecht, 2003). Natural fibers such as wool and cotton effectively absorb moisture from the skin, but they are unable to carry moisture to the clothing surface. Even worse, once the fibers absorb sweat, the weight of the clothing is increased. The absorption, known as "regain," has improved since synthetic fibers with wicking properties were invented. Clothing wicks sweat away from the body surface and reduces the overcooling effect (Gavin, 2003).

3.3 The technique of clothing layering system

Designing clothing for use in the cold environment has to consider thermal comfort. During the intensive activities, less clothing insulation is needed because additional heat is produced by the body. A temporary increase in heat production can be balanced by reducing the layers of clothing worn. The requirement of the layering system is to ensure that each layer has to be large enough to fit loosely over one another, and the clothing system consists of many layers to accommodate a variety of human activities (McCullought & Rohles, 1983; Giesbrecht, 2003).

The clothing system that has several layers regulates the thermal insulation. The layering system starts with a thin and breathable underwear fabric which wicks moisture away. This layer may be warm enough if the Celsius temperature is above zero and the wind is nonmoving. Below zero, a middle layer of lightweight fleece is added to keep the moisture away and provide insulation. The outer layer is a shell, made from waterproof and breathable fabric, which protects the body from wind and allows moisture transfer (Anonymous 2, 2004). The three-layering system is effective in the cold. The critical insulative property for a layering system is that the volume of warm air has to be trapped between the body and the outer garment. The number or bulk of layers is more important in determining thermal insulation rather than fiber composition. Also, the insulative layers at the knees, elbows, and shoulders should not be overly compressed. Otherwise, the volume of trapped warm air is removed. The insulative effect of the squeezed layers loses properties of retaining warm air (Gonzalez, 1995).

Although the layering system is a technique that effectively promotes thermal comfort during intensive exercise in cool conditions, McIntyre & Griffiths (1975) demonstrated in an experiment that the layering system did not completely improve comfort level. In their study, forty subjects were recruited. Subjects added woolen sweater over their clothes in cold conditions. Results showed that adding a woolen sweater increased the average perceived temperature by 2°C, but the feelings of discomfort did not change. Specifically, the subjects reported that their hands were warmer under the cold environment, but their feet still felt cold after donning the sweaters. The findings indicated that discomfort is likely to be correlated with cold feet (McIntyre & Griffiths, 1975).

3.4 The technology of electrically heated system

Haisman (1977) proves that handwear involving with electrically heated system improves thermal insulation of mittens. Haisman (1977) compared the conducting polymer mittens with knitted wire gloves and found that the hand temperatures of the conducting polymer mittens were slightly warmer, whereas the hand and finger temperatures of the knitted gloves remained at acceptable levels (Haisman, 1977). McCullough & Rohles (1983) reveal that mittens stop heat loss more effectively than gloves made of the same materials, even though mittens are usually considered as inconvenient to hand movement. Koscheyev, Leon, Paul, Tranchida, & Linder, (2000) further discover that electrically heated vests are more effective in keeping hands warm compared to mittens. The electrically heated vest prevents overcooling of the hands, and it is more effective in warming the torso and hands in cold conditions (Koscheyev *et al.*, 2000).

3.5 The technology of tubing system Sewn in Liquid Cooling/Warming Garments (SLCWG)

The newly developing technology, SLCWG, is an innovation in improving thermal comfort. SLCWG function to eliminate metabolic heat and perspiration. The tubing system sewn in SLCWG can be applied into design of commercial apparel products for intensively physical activities in the cold environment.

3.5.1 Function of SLCWG

Human activities in the cold environment range from general outdoor activities to extravehicular activities (EVA) in space. The protective strategy for the human body to resist the cold environments has to be thoughtfully and carefully planned. For instance, the space suit worn by astronauts for the explorative mission is a small, movable, and safe environment that protects astronauts from the hostile stresses of outer space and provides an atmospheric state similar to the earth (Nyberg, Diller, & Wisle, 2001). Thus, SLCWG are worn under the space suits to cool the astronauts when they perform outside space crafts. SLCWG integrates the Personal Life Support System (PLSS), a ventilation unit carried on the back to chill the circulating water (Darrow, 2004) (see Figure 1 and Figure 2). SLCWG works like a refrigerator that circulates water through a tubing system sewn in the garment. Body heat is transferred to the cool water that flows to the PLSS system where the water is cooled (Anonymous 1, 2004).

3.5.2 The tubing system of SLCWG

The space suits worn by astronauts protect them from hostile stress. SLCWG with tubes are the inner layers underneath of space suits. SLCWG are made of lightweight materials such as nylon spandex fabrics (Darrow, 2004). In order to optimize the performance of SLCWG, the placement of tubing pattern has to be considerably arranged. Xu, Herxamer, & Werner (1999) reported that a single-loop pattern, used to cool the whole body, is less effective than a multi-loop pattern. A single-loop tubing system overcools some areas of the body and undercools others during exercise. On the other hand, the multi-loop refers to a tubing system used to cool different individual regions of the body. Multi-loop cooling system is better than single-loop pattern to improve thermal comfort (Xu *et al.*, 1999). Ruckman, Hayes, & Cho (2002) also recommended the multi-loop pattern to cool certain regions independently. Cooling the surface of the individual working muscles, especially the leg muscles, provides greater thermal comfort during exercise (Ruckman *et al.*, 2002).

Figure 1: Liquid Cooling/Warming Garments (SLCWG)

Source: Anonymous 3 (2004)

Leon *et al.* (2004) tested changes in thermal conditions of the body areas using a series of tubing patterns. The core and skin temperatures, heat flux, blood flow to the extremities, comfort ratings, and thermal sensations determined the thermal conditions. Results showed that heat transfer among parts of the head, torso, forearms, and thighs was highly correlated. Therefore, areas where heat transfer is inefficient require less energy to operate, so volume of water circulation can be decreased (Leon *et al*., 2004). Once the body areas with less efficiency in heat transfer are identified, the water temperature is adjusted to save the energy for inefficient areas. The thigh and neck regions require the lowest water temperatures. The upper torso demands higher temperatures than the arms. Although a SLCWG well manages thermal balance of the human body, the tubes press bodies and cause discomfort in certain body areas (Xu *et al*., 1999).

4．Summary

The human body has limited capability to keep heat balance. Radiation, conduction, and convection are additional resources to help the human body maintain heat balance. Evaporation is a metabolic function of the human body that releases excessive heat by sweating. However, sweating is an inefficient way to get rid of excessive heat in the cold. If the moisture cannot completely be eliminated from the clothing, part of the heat remains and continues to slowly evaporate. This slow evaporation resulting from wet skin causes discomfort if the clothing is not dried quickly. Therefore, clothing is regarded as a barrier to evaporation and a disadvantage to thermal comfort.

The technology of tubing system sewn in an inner garment is efficient to eliminate sweat accumulation. SLCWG made of lightweight materials contain the tubing system to manage thermal balance during intensively physical activities. Body heat is transferred to the tubes circulated with cool water. In addition to SLCWG, the technique of clothing layering system has been promoted to resolve sweat problems. Also, other technologies such as the electrically heated handwears and vests are used by the military to eliminate sweat accumulation. Integrating the layering system with electrically heated one, the protective clothing may resolve the problem of tubes pressing on the body. The thermal comfort would be optimized if they layering system, electrically heated system, or tubing system of SLCWG is incorporated with one another

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