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# On the improvement of thermal comfort of university students by using electrically and chemically heated clothing in a cold classroom environment

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ABSTRACT

This study aimed to examine the effectiveness of two types of heated clothing (i.e., electrically and chemically heated clothing) in improving thermal comfort of university students while sitting in a simulated cold classroom environment. Eight male subjects performed three 90-min trials and three test scenarios were selected: EHC (i.e., electrically heated clothing), CHC (i.e., chemically heated clothing) and CON (i.e., the control, no heating). The trials were conducted in a climate chamber where the air temperature was 8.0 °C, RH = 80% and the air velocity was 0.17 m/s. Significantly higher mean skin (in both EHC and CHC) and body temperatures (in CHC) were found in the heated clothing compared to CON throughout the entire trials ($p < 0.05$). The whole-, upper- and lower-body thermal (TS) and comfort sensations (CS) were improved in the heated clothing (rated 'Neutral' and 'Comfortable', respectively, throughout the test) than CON (aggravated with time) ($p < 0.05$). Significantly higher finger temperatures (the 65–90th min, $p < 0.05$), finger blood flow (the 2–5th min in EHC and the 2–10th min in CHC, $p < 0.05$) and remarkably improved TSs at the hands and feet were detected in EHC and CHC than CON ($p < 0.05$). Finger dexterity was improved in CHC at the end of the test than the beginning ($p < 0.05$). CHC offered more heating benefits than EHC in terms of local skin temperature elevation at the trunk ($p < 0.05$). In summary, the heated clothing could serve as an effective method to improve both local- and whole-body thermal comfort of university students while sitting in cold classrooms.


## 1. Introduction

During cold winter season, many residential and university buildings in mountainous rural areas and Yangtze River urban areas in China are unheated [1,2]. University students have experienced cold discomfort at their ears, cheeks, hands and feet while sitting in unheated cold classrooms (below 10.0 °C) [3]. Some students have even developed cold related illnesses such as chilblain and pernio. It has been repeatedly pinpointed by researchers that cold discomfort and cold related illnesses were caused by the prolonged exposure in cold environments [4,5]. Students often have limited adaptive opportunities while having classes or examinations [6], i.e., they have to spend most of their time sitting around their desks and learning or dealing with examination papers. Hence, university students have less freedom to adjust their behaviors (such as adjusting activity levels and wearing more clothing) to maintain body heat balance. Cold classroom environments could induce thermal discomfort, impair manual dexterity and deteriorate the learning performance of university students [7,8]. Thus, it is important to seek effective methods to improve body thermal comfort while sitting in cold classrooms.

Since there is no HVAC system in the classrooms and university students had a rather constant activity level (i.e., sitting), a possible way to improve the body thermal comfort is to use personal comfort systems (PCSs). Heated chair [9], desk [10] or floor [10] that incorporated heating elements or panels [10,11] and radiation lamps [12] have been widely used to improve body thermal comfort in cool indoor environments. The effectiveness of such PCSs in improving human body thermal comfort in cold indoors such as offices and vehicles has been extensively examined [13]. PCSs were proved to achieve two benefits of improving thermal comfort and reducing the energy consumption of the HVACs [8–12]. However, the

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investigations were normally conducted in the indoor environments with the temperature of above 10 °C [13], the application of the results to colder classroom environments was unknown. Moreover, those PCSs were only targeted at one or several body local regions such as the face, back or/and bottoms. Larger heating area was often required to better improve the effectiveness of those PCSs in improving body thermal comfort. Nevertheless, more energy should be consumed and the cost-effect issue must be addressed.

Another possible way to minimize excessive body heat loss in cold environments is to wear high insulating traditional cold protective clothing [14] (i.e., passive heating) or wear clothing equipped with auxiliary heating [15]. Generally, traditional cold protective clothing has a multi-layer structure, and it was thick and heavy. Traditional cold protective clothing could restrict the human body movement, reduce the manual dexterity and thereby impair the human performance [16]. Moreover, it was infeasible to continuously increase the total thermal insulation by adding extra clothing layers because the clothing total insulation would probably reach an upper limit, i.e., around 4.3 clo [57]. Hence, the usage of traditional clothing to improve body thermal comfort has been limited in the event of extremely cold environments or long duration mild cold exposures [16]. To overcome the above problems, heated clothing implanted with auxiliary heating sources served as a promising choice to enhance cold protection [16]. Properly designed heated clothing has been proved to furnish human body with sufficient cold protection in cold environments without compromising body movement and burden [16].

Currently, heated clothing may be divided into four types, namely, electrically heated clothing (EHC), chemically heated clothing (CHC) utilizing the generated heat via chemical reaction provided by chemical substances, phase change heating clothing incorporated with phase change materials (PCMs) and air/fluid flow heated clothing [16]. Heated gloves and socks have been frequently examined and they have evidently demonstrated improvement in thermal comfort at the hands/feet and manual dexterity in unconventional cryogenic environments (e.g., extremely cold air or cold water) [16]. However, heated gloves and socks were insufficient to provide whole body thermal comfort due to a small heating body area [17]. In contrast, it was found that heated vests could improve the whole body thermal comfort, but with different improvement levels [18–25]. Choi et al. [18] investigated the effect of PCM incorporated clothing on human physiological and psychological responses while sitting in a cold environment (i.e., 5 °C and RH = 65%). The PCM incorporated clothing exhibited much higher microclimatic temperatures and improved thermal sensations than non-heated clothing, but it had no effect on the rectal and mean skin temperatures. Coca et al. [19] found that a liquid heated garment (LHG) could stabilize the rectal temperature and provide comfort during exercise. Also, the LHG with an inlet water temperature of 24 °C could assist the body rectal temperature to stabilize before exercise [19]. Flouris et al. [20] found that exercising in LHG induced a higher mean body temperature compared with the non-heating and pre-heating (in LHG before exercise) scenarios, which triggered more frequent episodes of cold-induced vasodilation (CIVD) in the extremities. Chan and Burton [21] examined the performance of a chemically heated clothing (CHC) set including a jacket equipped with 30 heating sachets and a pair of gloves with 4 chemical heating sachets. It was found that the CHC could maintain the torso skin temperature, but it had no effect on legs and feet of divers in cold water. Kirsi et al. [22] investigated the performance of an electrically heated vest in a very cold environment (i.e., −15 °C) while having subjects standing or doing light work. The vest could significantly raise local skin temperatures and improve the thermal sensation of the torso, but exerted a trivial effect on both core and extremity temperatures. The effectiveness of the heated clothing was highly related to its heating power and the exposed environmental temperatures [16]. For instance, Rantanen et al. [23] discovered that an electrically heated shirt was able to keep or increase the body mean skin temperature in an actual winter environment in Finland. However, the shirt was unable to maintain the skin temperature in extremely cold environments (i.e., −14 to −20 °C). Heated clothing with a large heating power was also found to be able to improve both local thermal comfort (such as promoted finger blood flow and dexterity) and overall-body thermal comfort when exposed to −25 °C for 3 h [24]. For heated clothing with a large heating power, local skin burns caused by overheating must be overcome [25]. Though not investigated, it was highly prospected that properly designed heated clothing could be able to improve both local and whole body thermal comfort of university students in cold classroom environments with no risk of local skin burns.

Thus, the main goal of this study was to examine the effectiveness of two newly developed heated clothing (i.e., chemically heated clothing [CHC] and electrically heated clothing [EHC]) in improving body thermal comfort of university students while sitting in a cold classroom environment. Human physiological and psychological responses in three clothing scenarios (i.e., non-heated traditional cold protective clothing, EHC and CHC) were examined and compared. Besides, manual dexterity tests were performed to investigate the effect of cold exposure on the finger dexterity of the subjects. It was hypothesized that both EHC and CHC could effectively improve thermal comfort of students while sitting in the selected cold classroom condition.

## 2. Methods

### 2.1. Subjects

Eight male, non-smoking university students gave their voluntary consent to participate in this study. To optimize the internal validity, exclusion criteria in this study were set as: getting flu in the week prior to participation, and any known history of diabetes, including hypertension, cardiovascular and esophageal diseases, and regulation medicine intake. Their average age, weight, height, body surface area and body mass index of participants were 23.0 ± 2.7 years, 61.8 ± 5.8 kg, 171.6 ± 3.7 cm, 1.73 ± 0.09 $m^2$ and 20.97 ± 1.70 $kg/m^2$, respectively.

The subjects were forbidden to drink alcoholic beverages or perform strenuous activities 24 h before the tests, and also not allowed to drink coffee or tea at least 2 h prior to the tests. Before giving both oral and written consent to participate, they were fully explained about the purpose, procedure and potential risks of the study. The study conforms to Ethical Committee of Soochow University for use of human subjects.

### 2.2. Clothing ensembles

Three clothing ensembles were examined: traditional cold protective clothing ensemble (i.e., CON), electrically heated ensemble (i.e., EHC) and chemically heated ensemble (i.e., CHC). The CON comprises underwear (i.e., long johns), a fleece jacket, a vest (worn as the outer layer), kneecaps (worn between the underwear and trousers), trousers, gloves, socks and shoes. A briefed description of the ensemble CON is displayed in Table 1.

The electrically heated clothing (EHC) and the chemically heated clothing (CHC) were developed by incorporating two kinds of heating elements into the vest and kneecaps. For EHC, five electrical heating pads were attached to the inner side of the vest (two at the waist, two at the scapula and one at the lower back), and two