Thermographic Assessment of Sweat Evaporation inside Clothing Systems

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Abstract
The purpose of the research project was to determine whether or not thermography can be used for assessing heat and moisture transport inside clothing systems worn by active duty police officers. An infrared camera system was used to identify temperature patterns over the body of healthy adult males performing controlled physical activities inside a temperature controlled environment. The thermographic documentation revealed complex temperature distribution patterns that were clearly associated with the regional evaporative cooling of sweat. Differences in the temperature patterns between subjects who produced large amounts of sweat and those who produced less sweat were observed. The study showed that thermography is an effective tool for assessing skin temperatures and sweat evaporation from clothing. The information gained can be applied to the design of new clothing systems to maximize the cooling effects of body sweat evaporation.

Key words: *thermography, sweat evaporation assessment, clothing systems.*

Introduction

Textile clothing systems frequently exhibit problems associated with moisture transport texture and drape, handling, metabolic heat retention, and washing. New textile technologies, however, are able to offer significant improvements in clothing comfort and safety while reducing the traditional shortcomings. Nevertheless, the actual comfort and safety of a garment designed to provide protection against excessive heat stress depends on the individual use of the garment under actual working conditions. Thermal protective clothing often requires the use of multi-layered ensembles where each layer performs a separate and specific function. Thus the performance of a garment system must be assessed not only for the overall assembly but also for each of the layers used.

Human subjects are frequently used for assessing the physiological and psychophysical impact of wearing garment systems under conrolled enviromental conditions. In the past, such studies have focused on the evaluation of sweat distribution over the body [1 - 3], the evaluation of physiological and psychological responses by different groups of subjects wearing similar garment systems (for example, male vs. female, young vs. old) [4 - 6], and evaluating the responses of subjects wearing different textile ensembles under moderate [7, 8] or under extreme environmental conditions [9 - 11]. Our previous investigations focused on the perceived comfort levels associated

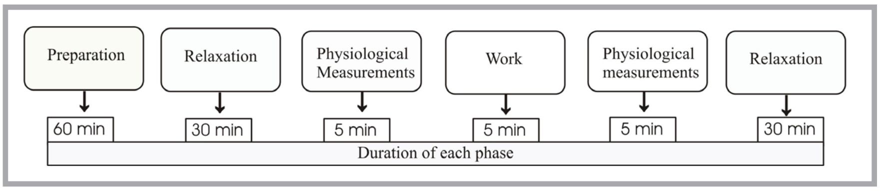


Figure 1. *Experiment protocol.*

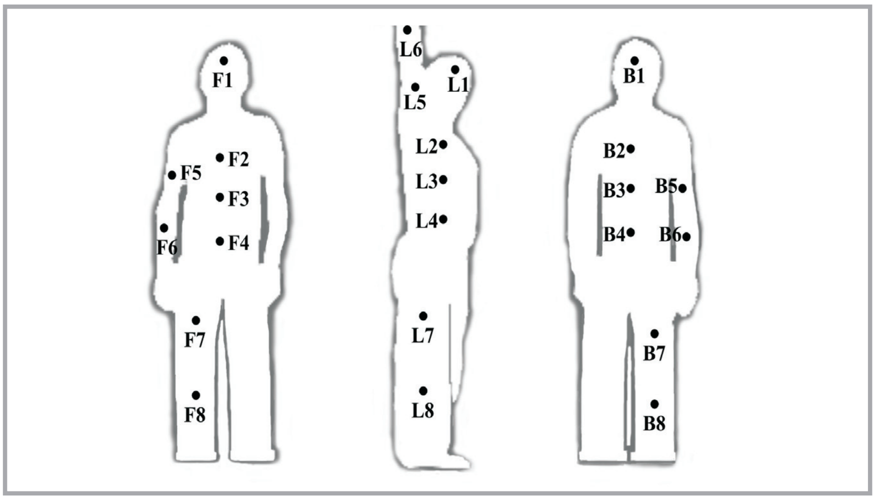


Figure 2. *Body reference locations: front (F), lateral (L), and back (B).*

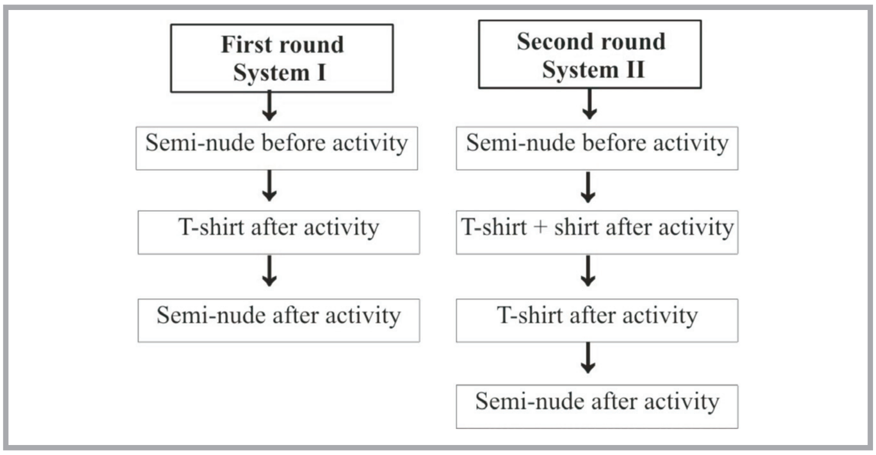
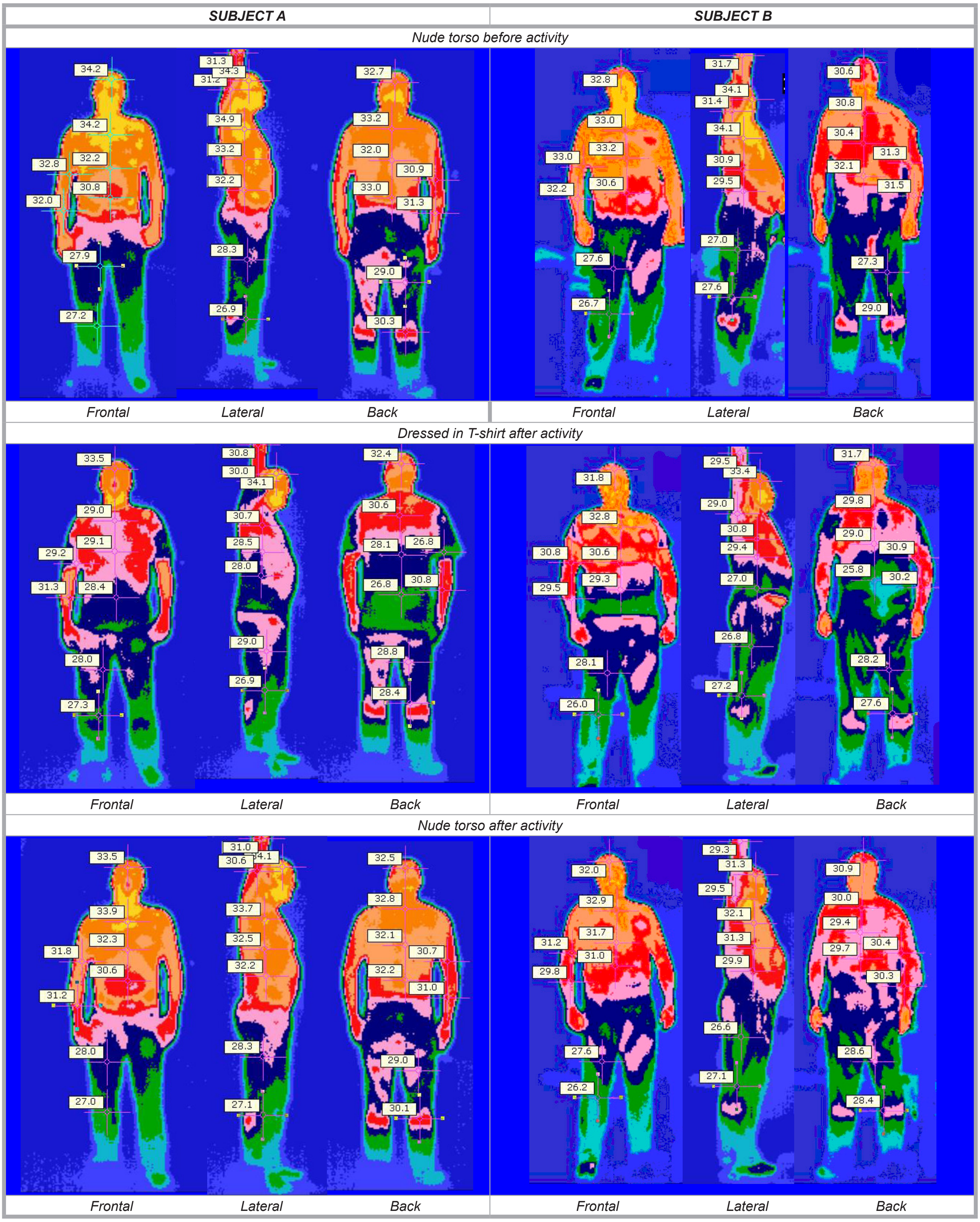


Figure 3. *Sequence of thermograms taken during the first and second trial.*

Table 1. *Thermograms taken during the first trial – System I.*

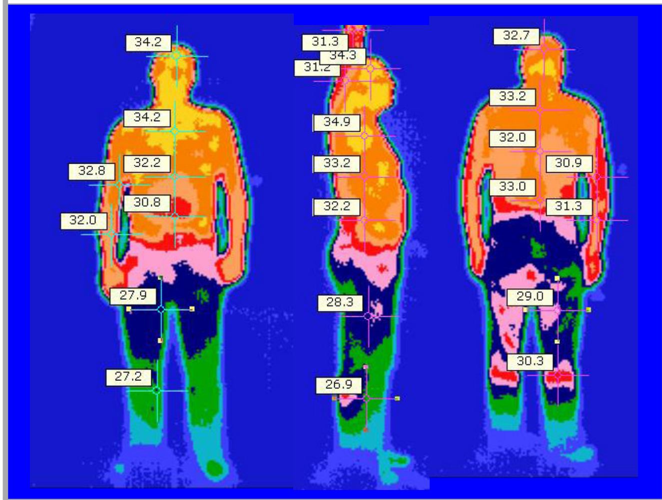


with wearing garments made of different fibers during exposures to moderate and hot environmental conditions [12 - 14]. In addition, comfort ratings using different methods [15] were compared to selected physiological indices [16]. The results reported here complement our earlier investigations using human subjects. The new data integrate subjective responses and temperature data that was obtained using thermography. The goal of our investigation was to ascertain the combined effects of heat and moisture transport in police uniforms on physiological and psychological responses of test subjects demonstrating moderate exertion under controlled environmental conditions.

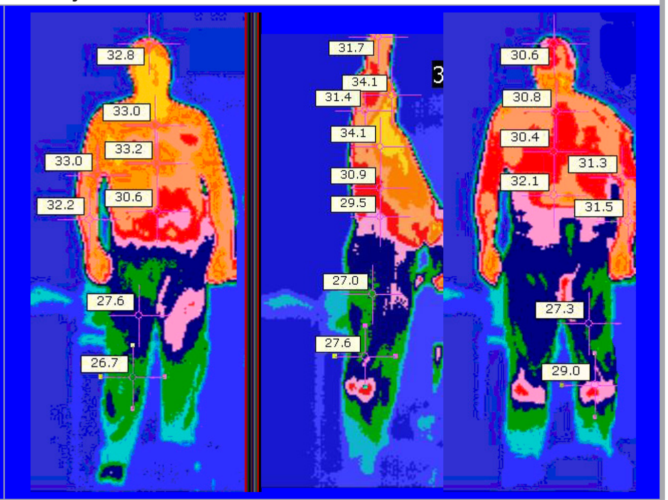
Table 2. *Thermograms taken during the second trial – System II.*

SUBJECT A	***SUBJECT B***

Shirt after activity

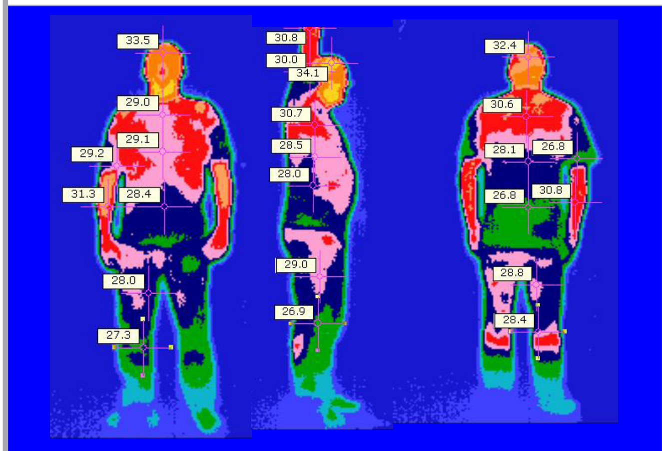


Frontal Lateral Back

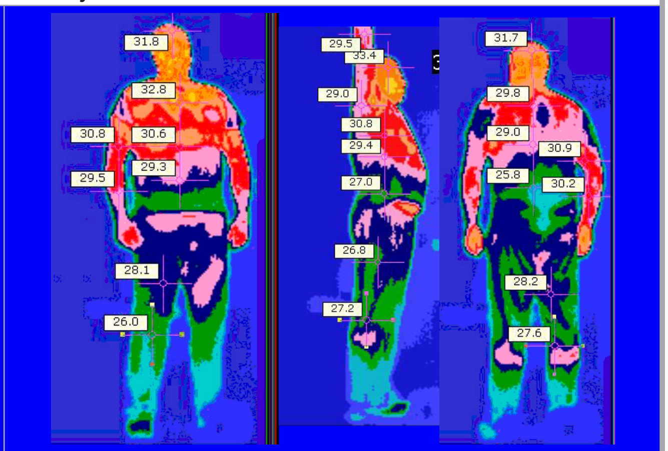


Frontal Lateral Back

T-shirt after activity

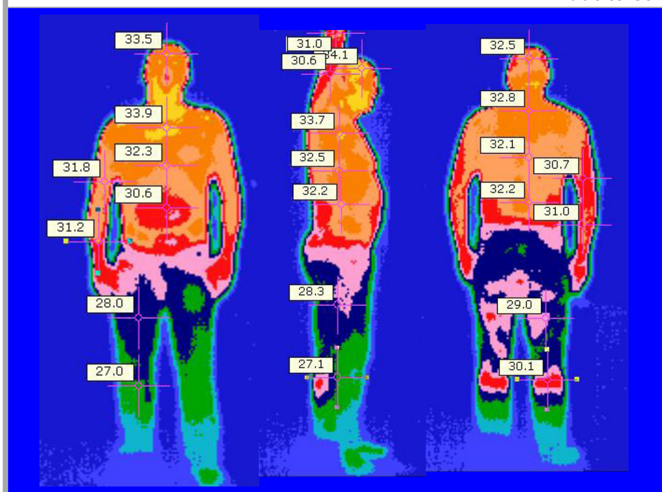


Frontal Lateral Back

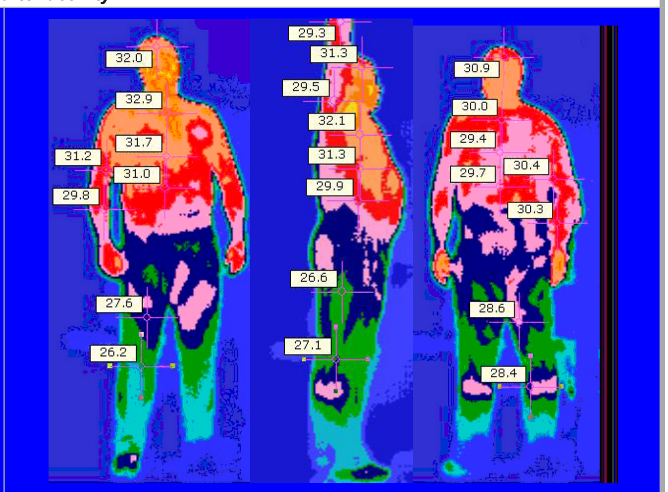


Frontal Lateral Back

Nude torso after activity



Frontal Lateral Back



Frontal Lateral Back

Methods and procedures

Nine healthy adult males participated as volunteer subjects in this study. All were active members of a police department. Their ages ranged from 35 to 46, their body weights from 92 kg to 140 kg, while their heights were from 171 cm to 192 cm. Prior to testing, all subjects underwent a general medical examination after completing a medical questionnaire as set forth by the ISO standard [17]. The questionnaire addressed heart disease, high blood pressure, pulmonary diseases, skin diseases and allergies, neurological and musculoskeletal problems, and use of prescription drugs. Blood pressure and heart rate were measured during testing.

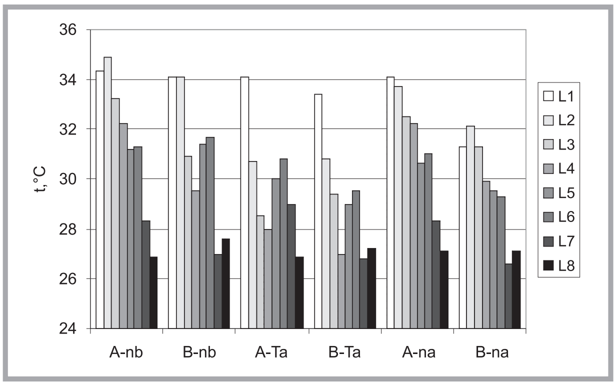


***Figure 4.** Temperatures of reference points on the frontal part of the body, first round.*

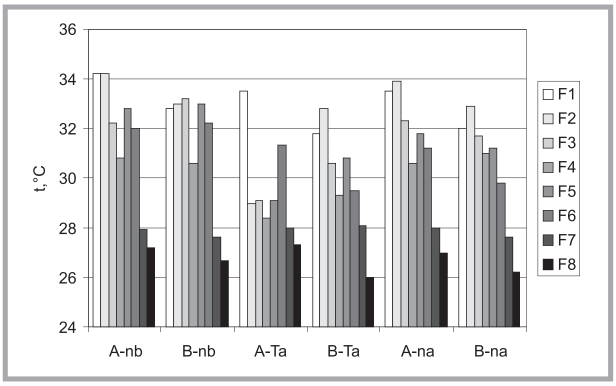


***Figure 5.** Temperatures of reference points on the lateral part of the body, first round.*

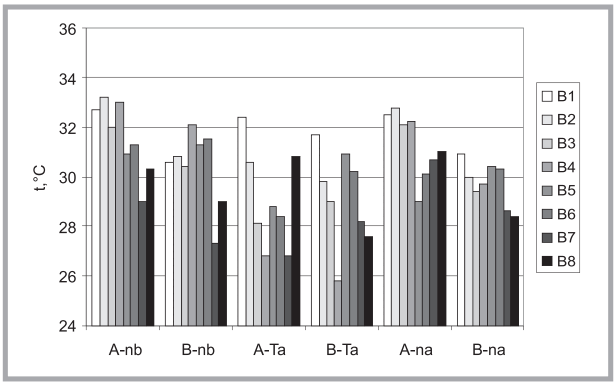


***Figure 6.** Temperatures of reference points on the back of the body, first round.*

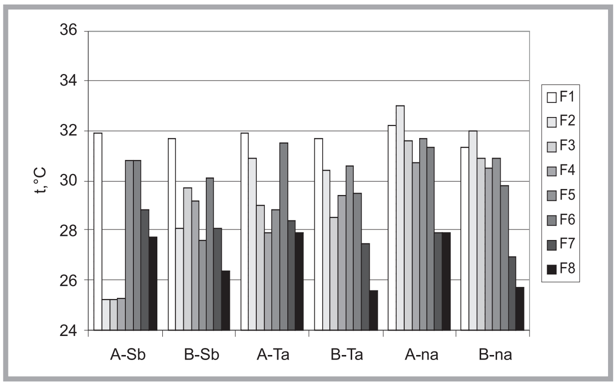


***Figure 7.** Temperatures of reference points on the frontal part of the body, second round.*

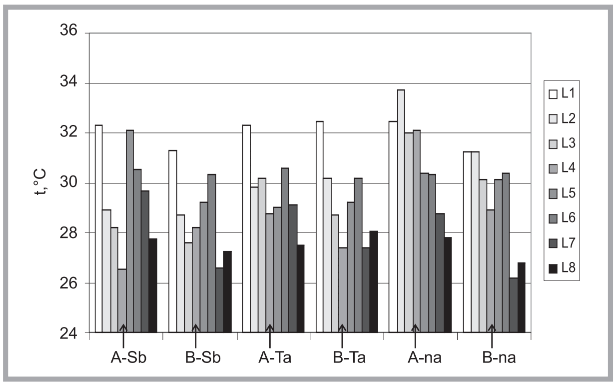


***Figure 8.** Temperatures of reference points on the lateral part of the body, second round.*

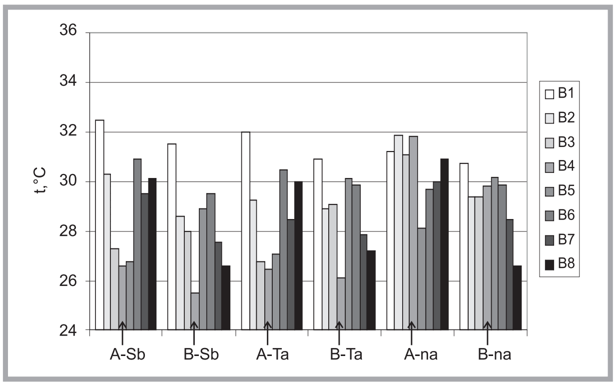


***Figure 9.** Temperatures of reference points on the back of the body, second round.*

All tests were supervised by a medical doctor.

Moderate physical exertion levels were used to generate metabolic heat. The tasks involved the following steps:
1. Lifting a 2 kg load from the floor and placing it onto a 1 meter high table surface
2. Resting for 5 seconds in a standing position
3. Removing the load from the table and placing it back onto the floor
4. Resting for 5 seconds in a standing position.

Work protocol was used for evaluating two clothing ensembles, designated as System I and System II. The two ensembles met pre-determined police department design and performance requirements. The thermal insulation characteristics of both garment systems were determined as 0.6 clo. Both systems were determined as being suitable for use in moderate thermal conditions and therefore were not expected to limit the physi-

***Table 3.** Legend for **Figures 6 - 11** and **Table 4**.*

Symbol	Description
A	Subject A
B	Subject B
nb	Nude torso, before activity
naT	Nude torso, after activity (wearing only T-shirt)
naS	Nude torso, after activity (wearing shirt and T-shirt)
Ta	T-shirt, after activity
na	Nude torso, after activity
Sa	T-shirt + short sleeved shirt, after activity

cal performance or safety of the police officers.

System I was 'casual' and consisted of trousers, a T-shirt, standard underwear, socks, and tennis shoes. System II was a 'classic' functional police work uniform consisting of the same components as used in System I, however, System II included an additional short sleeved shirt. All garments were made of 100% cotton. The work protocol is illustrated in ***Figure 1*** (see page 81).

A Flir P65 infrared camera was used for documenting surface temperature patterns on the body. This infrared camera is a non-contact device which detects infrared energy (heat radiation from the body) and converts the infrared radiation into an electronic signal which is processed to produce an image on a video monitor. The system also performs temperature calculations (Mijovic et al., 2009). The temperature sensitivity of the camera is 0.08 °C at 30 °C and the spacial resolution 1.3 mrad. The detector included a Focal Plane Array (FPA), a micro-bolometer with 320x240 pixels, and the range resolution was 7.5 to 13 µm.

24 reference locations on the body were selected to document the temperature patterns including the following: eight locations on the front of the body (listed as F points), eight locations on the left side of the body (listed as L points) and eight locations on the back of the body (listed as B points). These locations are illustrated in ***Figure 2*** (see page 81).

To assess the comfort or discomfort levels perceived in relation to garment temperature and moisture (sweating), each subject was asked to complete a standardised questionnaire. A 4-point scale (levels 1-4) was used which included the following boundary terms: comfortable-uncomfortable; hot-cold and dry-very wet. Separate thermograms were taken during the first trial, which involved garment System I. After the subjects rested, trial two started with garment System II. The sequence of thermograms taken during each of the two trials is illustrated in ***Figure 3*** (see page 81). To determine the amount of sweat absorbed by the garment, each garment component was weighed before and after each trial.

Results

Results are presented for the subject with the lowest sweat production observed and the subject with the highest sweat production observed. The subject with the highest sweat production is identified as Subject 'A' and that with the lowest sweat production is identified as Subject 'B'. The thermograms for Subject A and Subject B are illustrated in ***Tables 1*** and ***2***, (see page 82 & 83) respectively. Since there were no differences observed in the skin temperatures of the two subjects prior to engaging in the controlled physical activities, the semi-nude thermograms (nude torso only) are shown only in ***Table 1***, but should also be taken into consideration in ***Table 2***. Temperature distribution patterns for the two volunteer test subjects are illustrated in ***Figures 4*** through ***9***. The legend is given in ***Table 3***.

Table 4. *Index r_{st}*

Subject	r_{s35}			r_{s31}			r_{s28}		
	nb	naT	naS	nb	naT	naS	nb	naT	naS
A	0.11	0.04	0.01	0.02	0.04	0.05	0.15	0.12	0.17
B	0.06	0.00	0.00	0.02	0.12	0.17	0.12	0.13	0.11

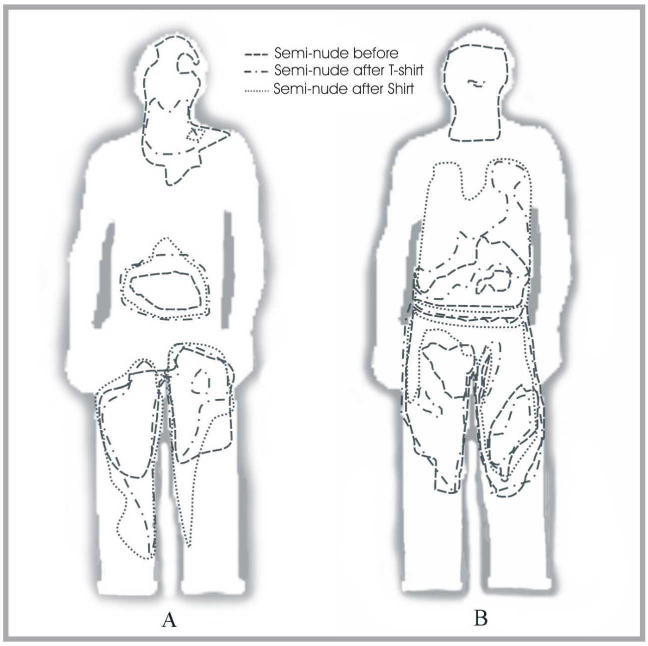


Figure 10. *Temperature zones for Subject A and Subject B.*

Dominant temperature 'zones' were observed for both subjects are illustrated in ***Figure 10***. These include the following: 35 °C in the head and upper chest area, 31 °C in the abdomen area and 28 °C in the upper leg area.

Dominant zones are used for the determination of the r_{st} index. Such an index is proposed which defines the ratio between the body surface area which exhibits a dominant temperature and the surface area of the whole body. The ratio is described as follows:

$$r_{st} = \frac{s_{zt}}{s_b} \quad (1),$$

where: r_{st} = ratio of surfaces with a dominant temperature and the surface area of the whole body, s_{zt} = surface area of a dominant temperature zone, s_b = surface area of the whole body.

The ratios associated with three specific temperature zones (t = 35, 31, 28 °C) on the head, abdomen and legs are given in ***Table 4***. Comfort ratings provided by the two subjects for heat and moisture conditions at the end of System I and System II trials are shown in ***Figure 11***.

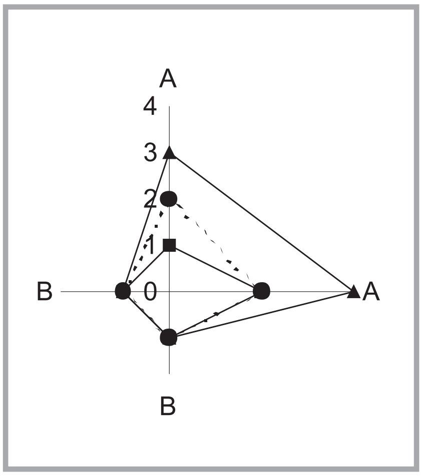


Figure 11*. Heat and moisture comfort ratings for Subjects A and B; vertical - System I, horizontal - System II, ■ comfort, ● heat, ▲ moisture.*

Discussion

The temperature distribution observed for Subject A, including the front of the torso at locations F2, F3 & F4, and garment configurations Sa and Ta are lower than those of Subject B. These differences can be explained by the higher amount of sweat accumulated by Subject A. The higher moisture content decreased the temperatures within the garment. Such temperature differences were even higher for clothing System II. While the differences among the temperatures observed for System I were between 0.9 - 3.8 ºC, those for System II were between 2.9 - 4.5 ºC. When the temperatures of the back are considered, it can be seen that Subject A had a temperature value at point B3 lower than that for Subject B; but the difference is not as great as seen on the front of the body. There are no systematic temperature patterns seen for the left side of the body and therefore should not be taken into consideration in future evaluations.

A comparison of the dominant body temperature zones reveals major differences in the abdomen and upper body regions. At the beginning of the trials, the zones of both subjects yielded the same index value r_{st} (0.02, ***Table 4***). However, once the physical activity began, the temperature zone for Subject B was three times larger than that for Subject A. As discussed earlier, the cause of this difference is the higher amount of sweat that was accumulated and distributed on the skin of Subject A. Therefore, the Index proposed could serve in future investigations as a comparative tool.

As shown in ***Figure 9***, Subject A reported higher levels of comfort for both System I and System II. The overall comfort reported by Subject A was lower than that reported by Subject B. However, Subject B reported similar levels of comfort for the two systems (level 1). Subject A considered System II less comfortable and acceptable than Subject B, especially with regards to moisture. Taking into account the thermographic images, it can be said that such a response would be expected due to a higher level of sweat absorption in the clothing systems. Considering these factors, it can be said that System II would not be appropriate for use by members of the police department who experience high levels of sweating during routine work assignments. This holds true even though both systems exhibit approximately the same levels of thermal insulation and similar levels of heat and moisture transfer.

A strong relationship was observed between the results obtained for the two methods employed in this study (objective and subjective methods). Therefore future studies related to this topic could focus only on one method as long as the conditions tested and the human subjects used in the trials are representative of actual work environments.

Conclusion

The thermographic assessment of skin and clothing temperatures involving human volunteer subjects revealed interesting temperature patterns that were clearly associated with regional evaporative cooling of sweat over the body. Differences in the temperature patterns for subjects who produced large amounts of sweat and those who produced less sweat could be easily differentiated.

Our application of thermography in the documentation of regional evaporative cooling from the skin and clothing provided an effective strategy for assessing complex temperature patterns that normally are associated with the human body during physical exertion under semi-nude and clothed conditions. In addition, the quantification of the thermograms allowed us to make temperature comparisons among the volunteer subjects.

The study clearly showed that thermography can serve as an effective instrument for assessing sweat evaporation from the skin and clothing. The temperature distribution patterns observed help identify body regions where evaporative cooling is most prominent and thus can be considered in the design of new garment systems that promote evaporative cooling, thus making a garment more comfortable and safer.

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