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Topic A7: Thermal comfort

IMPROVEMENT OF THERMAL COMFORT BY COOLING CLOTHING IN WARM CLIMATE

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SUMMARY

We developed cooling clothing that utilizes water evaporation and can adjust the cooling intensity according to the user's preference. The continuous cooling effect is supported by a small supply of clean water, and wet discomfort is prevented by using a textile with water-repellent silicon coating on the inner surface. We conducted experiments with human subjects in climate chambers maintained at 30 °C and RH 50% to compare the effectiveness of the cooling clothing with that of other convective cooling devices. The use of cooling clothing with a convective cooling device improved the subjects' thermal comfort compared to convective cooling alone. The supply of a small amount of water allowed the cooling clothing to provide a continuous cooling effect, whereas the effect of convective cooling alone decreased as sweat dried. However, the controllability of the cooling clothing needs to be improved.

INTRODUCTION

Clothing creates an individual microclimate around the human body. Removing excess (or wearing additional) clothing provides an effective solution for individual control of thermal sensations. However, clothing without cooling equipment cannot form a microclimate cooler than the surrounding environment. The latent heat for water evaporation is large (2417 J/g at

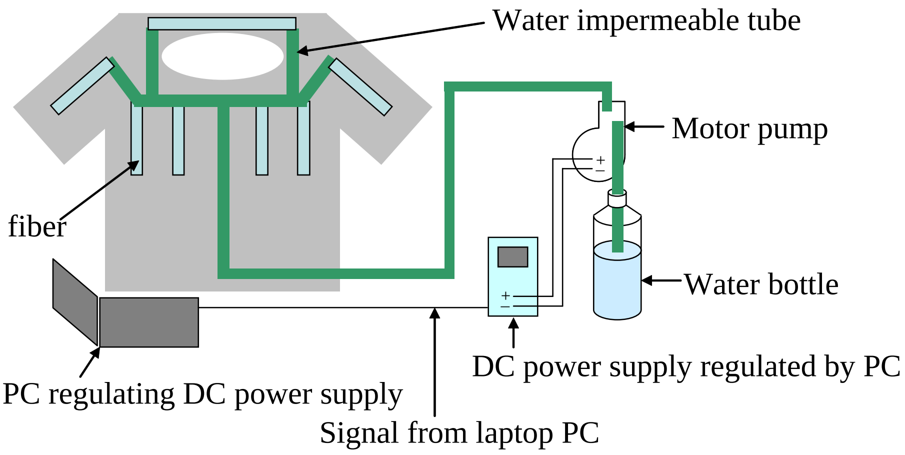

Figure 1. Construction of cooling clothing.

35 °C). We developed new cooling clothing (Sakoi et al. 2014) that can adjust the cooling intensity according to the user's preference and restrict wet discomfort through a textile with a water-repellent silicon coating on the inner surface. To solve the problem of wet discomfort, we propose a water control method in which the water supply rate is restricted to less than the water evaporation capacity under the applied condition.

We conducted experiments with human subjects in climate chambers to study the effect of our cooling clothing. We report some of the results in this paper.

METHODOLOGIES

Cooling Clothing System

Figure 1 shows our cooling clothing. Water is supplied to the outer surface of an undershirt from a small bottle by a small motor pump. A device that generates an airflow over the undershirt is simultaneously used to enhance evaporation on the outer surface of the shirt.

The enhanced convection produces evaporative cooling even in a high-humidity environment. The chest, front upper arms, and nape are cooled; water is supplied to the clothing surface in these areas. The cooled area is around 0.125 m^2. The output of the motor pump is regulated by a personal computer (PC). We assumed the typical thermal environment for application of the cooling clothing to be 29 °C and 60% RH; the convection equipment produced an enhanced airflow with a velocity of 0.84 m/s. The water evaporation capacity of the cooled body area (E_{max}) was determined to be 23 W (= 34.3 grams of water evaporated per hour) using Eq. (1).

$$E_{\mathrm{max}} = 16.5 h_{c.i} (P_{cl.i}{}^{*} - P_a) A_{.i} f_{cl.i} , \tag{1}$$

where E_{max} is the water evaporation capacity of the cooled body area [W], $h_{c.\mathrm{i}}$ is the convective heat transfer coefficient of the cooled body area [$\mathrm{W/m^2{}^\circ C}$], $P_{cl.\mathrm{i}}{}^{*}$ is the saturated vapor pressure at the clothing surface temperature for the cooled area [kPa], P_a is the environmental vapor pressure [kPa], $A_{.\mathrm{i}}$ is the cooled body area [m^2], and $f_{cl.\mathrm{i}}$ is the clothing area factor of the cooled area [−].

When the water supply rate is less than E_{max}, all of the supplied water evaporates and diffuses to the environment. If the supplied water exceeds E_{max}, the excess water accumulates in the shirt and cause dribbling. Considering the water supply capacity of the motor pump (0.57 g/s), we adopted the motor regulation method presented in Table 1, which does not cause water to accumulate in the shirt. The warm-up period was set to fill the inner space of the hollow fibers with water. During the output period, the user can adjust the water supply rate to four levels: stop, weak, medium, and strong. For E_{max} = 34.3 g/h, the strong water supply rate was determined to be 1.0 s/min (= 34.3⁄60 g/min was divided by 0.57 g/min). The power consumption of the motor pump was only 0.12 W for continuous operation.

Table 1. Output regulation of motor pump.

Regulation level	Warm-up period (0–16 s)	Output period (after 16 s)
Weak	Continuous	0.5 s/min
Medium	Continuous	0.75 s/min
Strong	Continuous	1.0 s/min

(a1) USBF in cond. 5.

(a2) USBF in cond. 1 & 2.

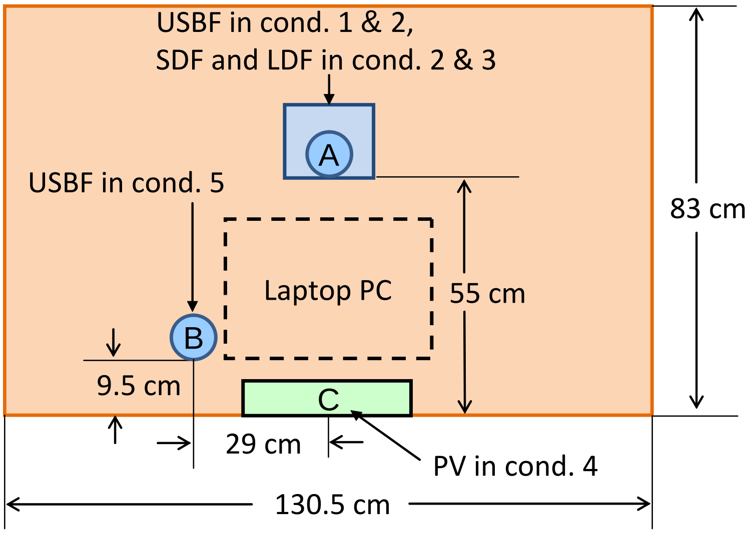

Figure 3. Locations of cooling devices at each work station.

(b) SDF (c) LDF (d) PV

Figure 2. Cooling devices used in experiments.

Experiments

We conducted experiments with human subjects in September 2012 to compare the effect of our cooling clothing with the cooling effect of four convective personal cooling devices: a USB fan (USBF) (i.e., a small fan operated by a USB power supply from a PC) (Fig. 2a), small desk fan (SDF) (Fig. 2b), large desk fan (LDF) (Fig. 2c), and personal ventilation (PV) supplying airflow upward tangentially to and/or against the subject's chest (Fig. 2d). The intensity of the USBF could be adjusted to three levels (off, I, and II) and had an oscillating function. The output intensities of the SDF, LDF, and PV could be regulated by a voltage regulator. The maximum power consumptions of the SDF and LDF were 25 and 50 W, respectively.

Twin climate chambers with separately controlled environments were used for the experiments. The air temperature and humidity in the chambers were maintained at 25 °C and 50% RH or 30 °C and 50% RH. We assumed that under the former conditions, subjects would be comfortable without any cooling devices; under the latter conditions, the subjects would want to use a cooling device to alleviate their thermal discomfort. Each chamber had two desks arranged with the cooling devices, as shown in Fig. 3.

Table 2. Experimental conditions.

Condition	Surrounding environment	First device	Second device
1	25 °C, 50 % RH	USB fan without rotation, directed to face	USB fan with rotation, directed to face
2	30 °C, 50 % RH	USB fan without rotation, directed to face	Small desk fan without rotation, directed to face
3		Large desk fan without rotation, directed to face	Large desk fan with rotation, directed to face
4		Desk personalized ventilation, with tangential airflow	Cooling clothing and desk personalized ventilation, with tangential airflow
5		USB fan without rotation, directed to chest	Cooling clothing and USB fan without rotation, directed to chest

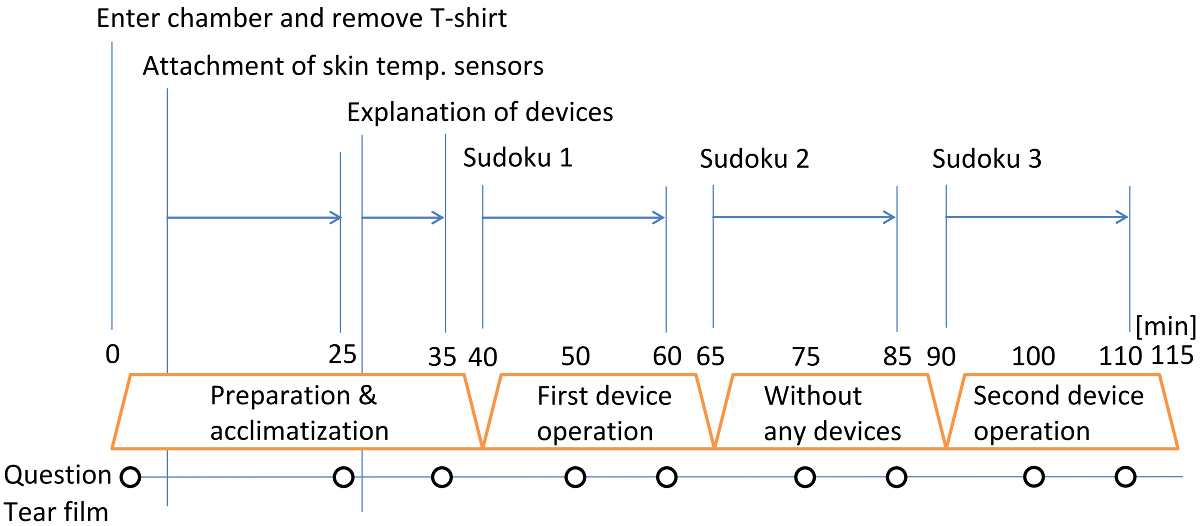

Figure 4. Experiment schedule.

Twenty healthy male students participated in the experiments. The subjects wore their own light trousers, undershorts, socks, and shoes; they also wore a T-shirt (underwear of cooling clothing) prepared by us. The intrinsic clothing thermal insulation was around 0.43 clo.

The experimental conditions are listed in Table 2. Each subject participated in one experiment a day for five experiments in total under different conditions. Two subjects stayed in each chamber. The two workstations were separated by partitions to diminish their influence on each other. The experimental procedure is shown in Fig. 4. During each experiment, the subjects were exposed to two cooling devices. The order of exposure to the cooling devices was randomized. In conditions 1 and 2, the USB fan was set on the desk at location A (Fig. 3) in front of the subject. The airflow direction was fixed to the face of the subject. In condition 5, it was set to location B (Fig. 3), and the airflow generated by the fan was directed toward the chest of the subject across the left forearm. The SDF of condition 2 and LDF in condition 3 were set to location A (Fig. 3), and the airflow was directed toward the face. All fans set to location A were lifted to the height of the subject’s face. The PV was installed at the edge of workstation (location C in Fig. 3). The subjects could also adjust the direction of the supplied PV airflow.

The exposure time was 115 min and comprised four sessions: (1) preparation and acclimatization to the surrounding environment without using any cooling devices, (2) use of the first cooling device, (3) re-acclimatization to the surrounding environment without using any cooling devices, and (4) use of the second cooling device. After the preparation (change of clothing and attachment of sensors), subjects sat at the workstations. The subjects controlled the cooling devices in the first and second sessions in accordance with their preferences.

During the exposure, the subjects played the game Sudoku on a PC. Periodically, the subjects responded to a computerized questionnaire with regard to the thermal sensations of their whole body and the acceptability according to the scales listed in Table 3. The order of activities that the subjects were involved in during the exposure are shown in Fig. 4. The subjects were permitted to freely drink water from a 500 cc bottle. The bottles were kept in the chamber for more than 1 h prior to the experiment to make their temperature the same as that of the surrounding environment.

Table 3. Scales of thermal sensation and acceptability.

Thermal sensation	Acceptability
+3: hot	+1: clearly acceptable
+2: warm	+0: just acceptable
+1: slightly warm	−0: just unacceptable
0: neutral	−1: clearly unacceptable
–1: slightly cool	
–2: cool	
–3: cold	

The skin temperatures of the forehead, upper chest, lower chest, and back and the clothing surface temperatures at the upper and lower chests were measured and recorded with thermistors. The subjects responded to the questionnaire (Table 4) on their impressions of the cooling clothing and the other cooling systems, their controllability, and how quickly they could feel the provided cooling when adjusted.

Table 4 Scale of impressions

Speed to feel cooling effect	Controllability
Immediately	Easy
After some time	A bit easy
No change	Difficult
	Very difficult

RESULTS AND DISCUSSION

For the thermal sensation and acceptability, we analyzed the data reported in the last 5 min of each session because the subjects were sufficiently acclimatized to the conditions by then. We conducted analysis of variance (ANOVA) and then applied multiple comparisons using the least significant difference. These analyses were conducted using js-STAR 2012 (Tanaka and

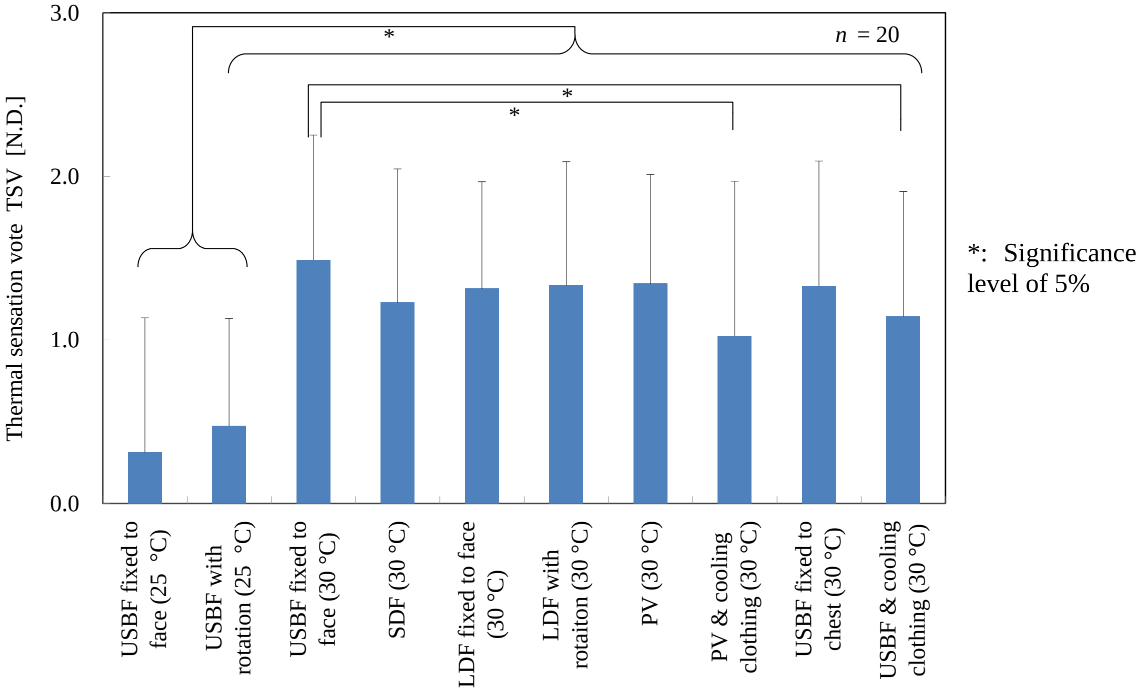

Figure 5. Thermal sensation of whole body in each session.

Nakano, 2012). Figures 5 and 6 show the mean thermal sensation and acceptability votes of the 20 subjects and their standard deviations. The significant differences ($p < 0.05$) in the results are indicated.

Figure 5 shows the thermal sensation for each session. The thermal sensations were significantly cooler at 25 °C than at 30 °C. In the sessions at 30 °C with cooling, the thermal sensations reported for simultaneous use of the PV or USBF and cooling clothing were significantly lower than those when USBF was fixed to provide airflow against the face alone.

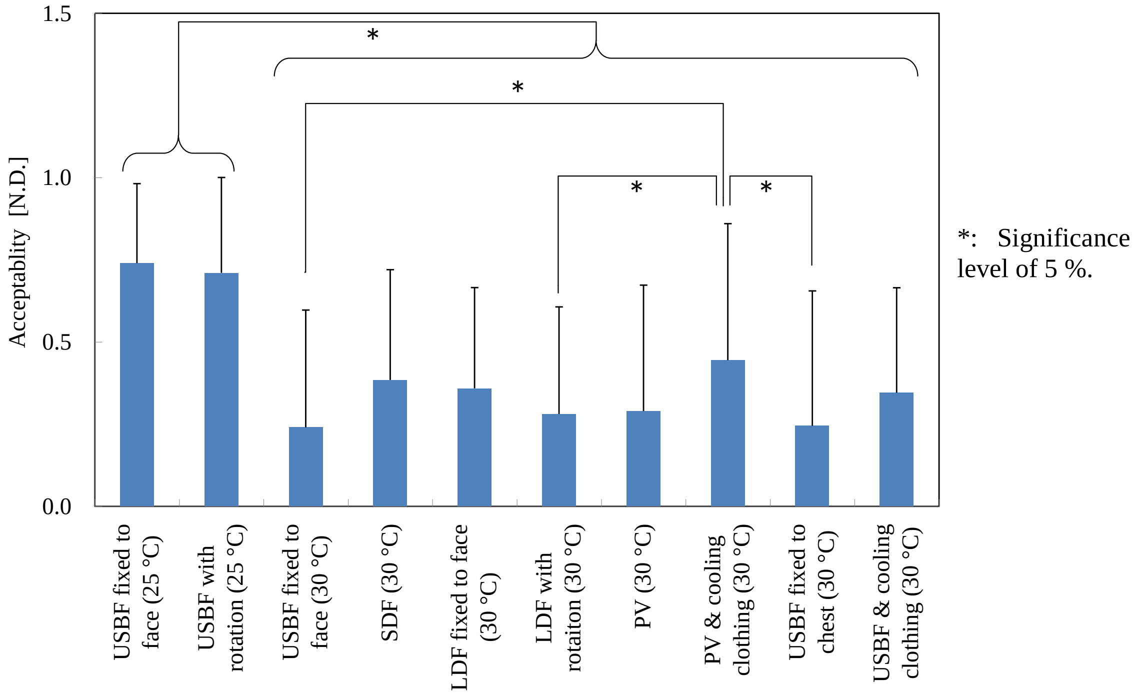

Figure 6. Acceptability in each session.

At 30 °C, the lowest thermal sensation was reported for the simultaneous use of the PV and cooling clothing (1.0) followed by the simultaneous use of the USBF and cooling clothing (1.1) and the SDF alone (1.2). Thus, the cooling clothing lowered the thermal sensations.

Figure 6 shows the acceptability for each session. The acceptability was positive for all sessions. The acceptability was significantly higher at 25 °C than at 30 °C. In the 30 °C sessions, the simultaneous use of PV and cooling clothing was significantly more acceptable than the USBF fixed to the face, LDF with oscillation, and USBF fixed to the chest. At 30 °C, the highest mean acceptability was reported for the simultaneous use of the PV and cooling clothing (0.45) followed by the SDF (0.38), LDF fixed to the face (0.36), and simultaneous use of the USBF and cooling clothing (0.35). The acceptability of the thermal sensation increased when the convective cooling devices were combined with the cooling clothing.

Because of space limitations, the data on the measured skin temperature and clothing surface temperature are not reported in detail. However, the data showed that simultaneous use of the PV or USBF with the cooling clothing had a continuous cooling effect, whereas the cooling effect decreased with time when the convective cooling devices were used alone. This was caused by the decrease in evaporation cooling as sweat dried.

Figure 7 compares how quickly subjects could feel the cooling effect of each cooling device when they controlled them. The cooling effect of the convective cooling systems was felt quickly except for the USBF, which had a low cooling effect. The cooling response was slow when the cooling clothing was used. This can be explained by the time lag between water diffusion and evaporation. For the cooling clothing we developed, improving the response speed is difficult because the cooling intensity is controlled through adjustment of the water supply rate.

Figure 8 shows the controllability of each cooling system. The subjects felt that the traditional convective cooling systems were easy to control. The PV had two outlets (airflow could be

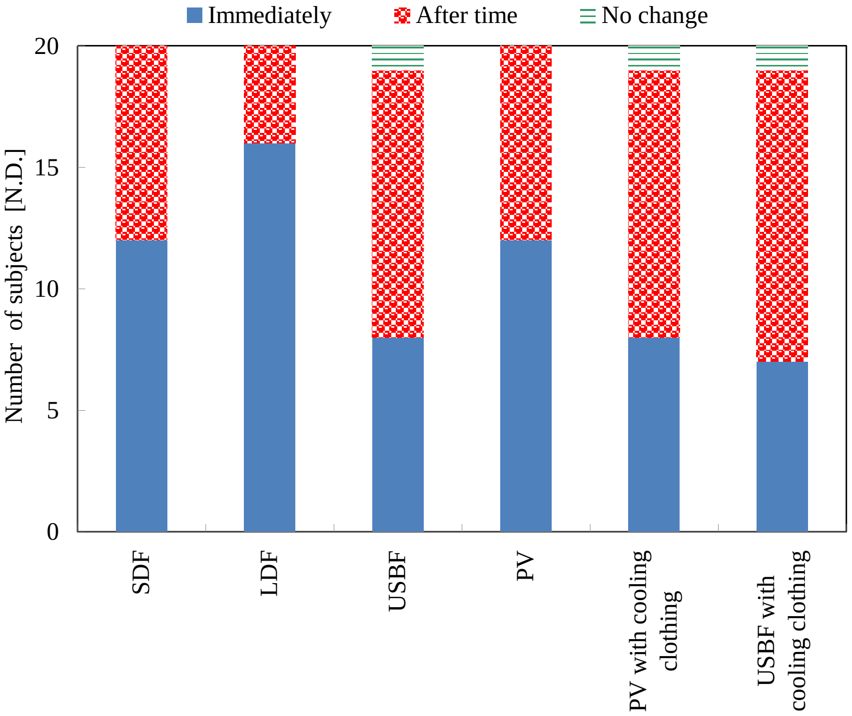

Figure 7 How quickly the cooling effect of each system was felt

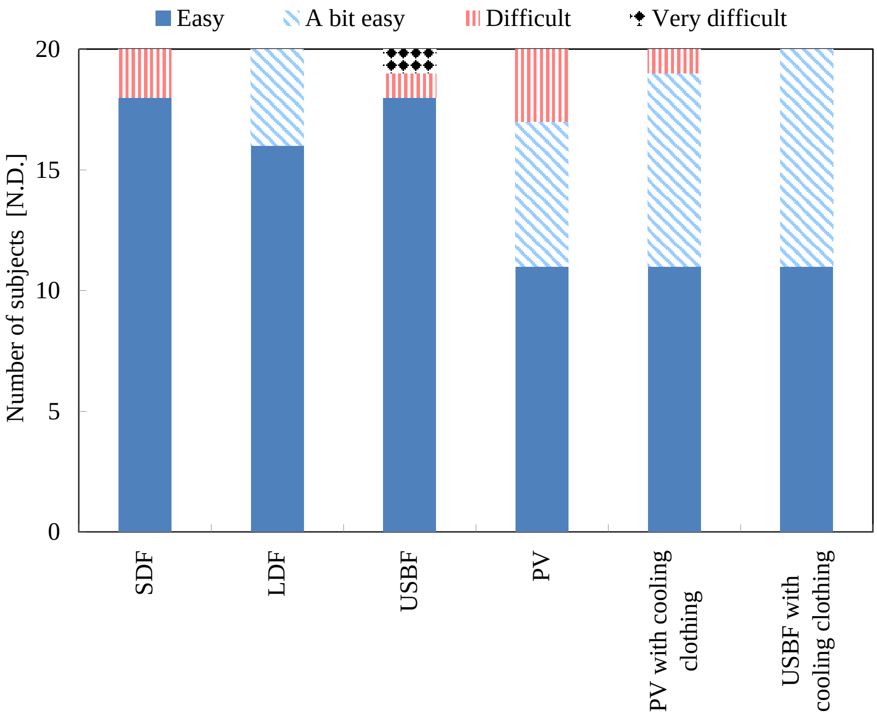

Figure 8 Controllability of each system

supplied upward against the face and/or horizontally against the chest), and the subjects needed to control the directions of the two outlet flows; thus, they felt that it was relatively difficult to control. Controlling the PV or USBF combined with the cooling clothing was difficult compared to the control of the traditional convective cooling systems. The subjects controlled both the intensity of the PV or USBF and the water supply rate of cooling clothing simultaneously. To improve the controllability, an automatic coupled control method for the PV/USBF and cooling clothing is required.

CONCLUSIONS

We confirmed that our cooling clothing improves thermal comfort in warm climates when operated in conjunction with convective cooling devices. However, its controllability needs to be improved and will be the subject of future research.

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