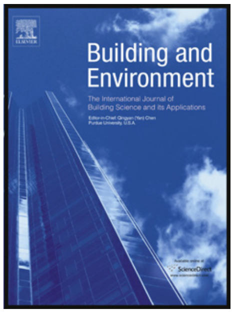

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Effects of temperature steps on human skin physiology and thermal sensation response

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Abstract

Air conditioning is frequently used as a means of adjusting indoor thermal environment in hot-and-humid areas. However, when entering an air-conditioned building from outdoors people may experience thermal discomfort and risk health consequence if the instantaneous change of air temperature exceeds the thermoregulatory capacity. A study was conducted to investigate the alteration in thermal perception and in thermoregulation that simultaneously occurred in response to temperature step in a thermal transient. In this study, two temperature down-steps from 32/28 to 24^{o}C and an up-step from 20 to 24^{o}C were created in a climatic chamber consisting of two microclimate-controlled rooms, and subjects were evaluated for change in thermal sensation as well as in skin physiological properties, including skin capillary blood flow (SCBF), skin moisture, transepidermal water loss (TEWL), and skin temperature over the course of acclimation. As the results show, a cold sensation overshot occurred in thermal sensation vote (TSV), skin temperature, and SCBF in one min after the temperature dropped from 32 to 24^{o}C. TSV correlated the best with skin temperature (r = 0.60) and moderately with skin moisture and TEWL (r = 0.42-0.54) when the temperature down-step reached 8^{o}C. TEWL acclimated in a two-stage pattern, demonstrating a difference between the sensational change and thermoregulation. The gender-specific influence occurred in thermoregulation but not in subjective sensation. The findings of the study suggest that thermoregulatory burden might be adequately controlled when the temperature step in thermal transition zone is limited to 4^{o}C or lower.

Keywords: Temperature step; Climate chamber experiment; Skin physiological indicators;
Transepidermal water loss; Thermal sensation; Transient thermal comfort

1. Introduction

1.1. Background

In Taiwan, air-conditioning is the most frequently used means in adjusting the indoor thermal environment to accommodate the hot-and-humid climate. For occupants working or living in the air-conditioned buildings, they constantly encounter a step change in air temperature when entering or leaving the buildings, sometimes at a substantial level in hot summer days. The instantaneous change in temperature can bring discomfort or even risk a thermal stress, such as contracting a cold, to those who have to regularly move across the temperature ramp. To alleviate human physiology from the thermoregulatory shock arising from sudden change in thermal environment, the temperature step in the thermal transition zone of a building, including the entrance area, foyer, atrium, lift lobby, and etc., should be appropriately controlled. The control of transient temperature also allows for an opportunity to decrease the consumption of energy used in air-conditioning the transitional space. Chun and Tamura [1] estimated that the energy used in some transition spaces could be up to three times higher than the level spent in the other enclosed spaces. To better characterize the human responses upon an abrupt thermal challenge, we reported here a study conducted in climatic chamber that evaluated the synchronous modification of subjective thermal sensation and skin physiology in adaptation to up- and down-step changes of air temperature.

1.2. Thermal comfort in thermal transient

The thermal comfort in transient conditions has been a focus of studies and literature reviews [2,3]. de Dear et al. [4] investigated the conscious experience of thermal transients both experimentally and by means of dynamic thermoreception modeling. In their observation, the immediate sensations following temperature up-steps closely resembled the steady-state responses established later in the warmer environment, whereas the initial impressions from temperature down-steps were typically twice the magnitude of their up-step counterparts. The heightened subjective sensitivity to temperature down-step was interpreted via modeling as a result of lesser cutaneous depth of the cold thermoreceptors compared to that of their warm counterparts. Similar phenomena were described in the ISO EN 7730 -2005 [5]: when a temperature step in the operative temperature occurs, a new steady-state thermal sensation is experienced immediately after an up-step, but upon a down-step change the sensation may plummet initially to a level beneath that predicted by the PMV, followed by gradual return to a stable level in about 30 min.

Nagano et al. [6] in their experiment, adopting a twin-climate-chamber design, exposed male subjects to a 34 or 37^{o}C condition and then transferred the subjects to a cooler environment. The thermally neutral temperature was found to decline continuously even 50 min after the temperature drop. In addition, an overshot of thermal sensation in response to the temperature down-step was also observed. Hwang et al. [7] investigated the immediate thermal response of guests to temperature steps when entering a business center from outdoors, and reported that the experience of sudden temperature change resulted in an increase in guest aspiration. In Japanese underground shopping malls where shoppers were exposed to continuous temperature change when moving across different spaces, Chun and Tamura [8] observed that the temperature change was one of the most important factors affecting human thermal comfort. In a different study, Chun and Tamura [1] evaluated the thermal comfort of test subjects during a sequenced walk through a controlled environmental chamber, and demonstrated that the thermal comfort in a transitional space was closely associated with the thermal environment the subjects were exposed to. Zhao [9] in experiments conducted in environmental chambers found that the users of space were thermally over-sensitive during the adaptive period when the temperature ramp between two chambers exceeded 5.0^{o}C. These studies demonstrated that the human thermal sensation might change rapidly when challenged by a temperature transient and then gradually reach a new steady state..

1.3. Skin physiology as indicators of thermoregulation and thermal comfort

When the status of thermal environment alters, human bodies acclimate by metabolic adjustment and thermoregulation to compensate for the change in heat transfer between the body core and the surroundings so to maintain thermal balance [10,11]. The excess body heat produced in response to thermal loading of the environment results in an increase in the body core temperature, driving the thermoregulatory center in the hypothalamus to signal transmission of the body heat through blood flows and tissues to the skin. Once reaching the skin surface, the heat is dissipated via vasodilation of blood vessels and subsequent perspiration, and the body gradually returns to homeostasis. However, if the thermoreceptors sense a strong stimulus, such as those received in response to a sudden change in temperature, and call for a significant heat transfer, the thermoregulatory system may not effectively react to the cooling requirement. As a result, the thermoregulatory system may be overloaded and even disrupted.

Conventionally, the effect of thermal environment to indoor occupants is gauged using the survey technique, in which a questionnaire such as those resembling the ASHRAE Standard 55 questionnaire [12] is employed to rank the subjective perception of thermal comfort. As an intuitive approach, however, the questionnaire-based survey is inherently limited from delineating the physiological processes involved and their significance in thermal adaptation, rendering the evaluation of thermal strain incomplete as far as thermoregulatory capacity is concerned. The core temperature, heart rate, and sweat rate are among the physiological properties frequently applied in thermal stress/comfort assessments [13,14]. The core temperature and heart rate are often taken as a measure of thermoregulation. However, driven by the perception registered through thermoreceptors situated in the skin, they largely react to the requirement of thermoregulatory adjustment as induced by the temperature of the skin and the blood flow in the hypothalamus [15,16] rather than serve as indicators of the physiological events evolving during thermoregulation. The sweat rate signifies the final stage of thermoregulation, however, it does not enable a temporal interpretation of the thermoregulatory processes in progress. Alternatively, the skin temperature has been extensively used as a physiological indicator in the assessment of thermal stress/comfort [6,17-19] and in constructing physiologically equivalent index of thermal comfort for application in the biometeorological assessment of thermal environment [15,16,20].

In recent years additional skin physiological properties involved in thermoregulation have been attempted in evaluating the thermal comfort of human subjects. The vasodilation and congestion of skin capillary vessels in response to requirement of heat dissipation results in an increase of blood perfusion in the skin tissues and directs the change in skin moisture and sweat secretion. Manifested as the redness of the skin, the change in skin capillary blood flow (SCBF) can be quantified using laser Doppler-based perfusion monitoring/imaging techniques [21] and has been applied as an endpoint in diagnosing the response of skin microvasculature to thermal challenge, e.g., the constriction of arteriovenous anastomoses in fingers/hands following cold provocation [22,23] or dilation due to local heating [24]. The skin moisture indicates the level of hydration in the stratum corneum and viable epidermis. Maglinger et al. [25] investigated the effect of surgical drape on evaporative heat loss of human subjects using thermal flux transducers, and observed a greater loss of body heat from the skin surface in association with higher skin moisture when the skin was covered with the drape. The involvement of skin moisture change as an intermediate stage in body heat loss suggests a role of this property to elaborate on the dynamics involved in thermoregulation as the body adapts to thermal environment change. The transepidermal water loss (TEWL) describes the invisible evaporation of water from the skin surface, and quantitatively expresses the water loss as a rate of vapor formation across the stratum corneum and epidermis in healthy skin [26]. The TEWL is routinely employed to evaluate the functions of epidermal permeability barrier under either normal, experimentally perturbed, or diseased conditions [27,28]. Chen and Wu [29] in a climatic chamber study investigated the levels of TEWL and skin temperature in the dorsal skin of human forearm in relation to different combinations of air temperature and relative humidity, and observed that the TEWL increased linearly in response to increasing air temperature at levels above 25^{o}C. These observations suggest that the SCBF, skin moisture, and TEWL may be applied as a complement to the skin temperature in describing human subjective sensation and physiological adjustments occurring in response to step change of temperature in the thermal transition zone, particularly on how different thermoregulatory events take place to satisfy the demands of thermal adaptation and balance.

1.4. Study goals

The study presented here evaluated the change in subjective sensation and thermoregulation when humans were confronted with instantaneous change in air temperature. The specific aims included: 1) evaluating the temporal changes in thermal sensation and selected skin physiological properties in acclimation to a temperature up- or down-step; 2) investigating the gender-specific differences in subjective perception and thermoregulatory events following a temperature ramp; 3) examining the consistency between the adjustment in subjective thermal comfort and that in skin properties in response to a thermal challenge. Our goal is to demonstrate the thermoregulatory events occurring in response to temperature step so to facilitate proper consideration of thermoregulatory capacity in the design or modification of thermal transient in climate-controlled buildings.

2. Study design and methods

2.1. Study design

This study simulated the initial stage of people entering an air-conditioned thermal transition zone from an outdoor space of a thermal status colder or warmer than that of the indoor thermal transient. In the study, experiments were conducted in a climatic chamber consisting of two adjacent climate-controlled rooms that each could be individually controlled for environmental variables, including air temperature, relative humidity (RH), air velocity (Vair), and radiant heat. The chamber allowed for adjustment of the air temperature, RH, and Vair in the range of 18-40^{o}C (±0.5^{o}C), 40-90% (±5%), and 0-1m/s, respectively. When equilibrated the spatial discrepancy of air temperature in the chamber was less than ±0.2^{o}C. The twin climate-controlled rooms were used to create two distinct zones of air temperature, one representing the ambient environment (hereafter referred to as the “outdoor chamber”) and the other the thermal transient inside an air-conditioned building (“indoor chamber”). The outdoor chamber has a dimension of 4.1 m (length) × 3.6 m (width) × 2.6 m (height) and the indoor chamber a dimension of 4.1 m (length) × 2.6 m (width) × 2.6 m (height). Both chambers were immediately adjacent to each other and connected by a door. The connecting door allowed the subjects and two carts loaded with portable equipments measuring physiological properties to enter the indoor chamber from the outdoor chamber; otherwise the door remained closed when experiments were in session. The temperature transient was replicated when test subjects moved from the outdoor to the indoor chamber. The air temperature applied in the outdoor chamber was 20, 28, or 32^{o}C, while the temperature in the indoor chamber was kept a constant 24^{o}C, producing a temperature step of 4, -4, and -8^{o}C as the subjects moved into the thermal transient. The indoor temperature of 24^{o}C represented a thermally neutral environment. The outdoor temperatures of 20 and 28^{o}C were selected to represent the ambient temperatures commonly encountered in the cold and warm seasons in Taiwan, respectively, whereas the value of 32^{o}C chosen to simulate the temperature in the summer [7]. The RH in both rooms was maintained at approximately 60% throughout the study. The Vair was less than 0.2 m/s, and the mean radiant temperature was approximately the same as the air temperature.

2.2. Subject characteristics

A total of 16 subjects were recruited to participate in the study, including 8 males and 8 females. The subjects were all undergraduate or graduate students of an age between 18 to 22 years old. Table 1 shows the distribution of their anthropometric data. Every subject participated in all experimental sessions. Preliminary evaluation of the subjects was conducted to exclude those who might suffer skin diseases and disorders or might be using skin medicinal products known to interfere with the evaluation of skin physiology. The subjects were briefed on the purpose, design, and experimental procedures of the study, and an informed consent was obtained from each of them. The subjects were prohibited from applying sunscreens, lotions, skin care products, or pharmaceutical products of therapeutic effects (e.g., lotions applied for skin hydration or containing nutrients for erythemal reduction) at the site of skin physiology measurement (i.e., the dorsal skin of left forearm) during the course of study.

2.3. Experimental procedures

For each experimental session, the subjects were required to maintain regular activities the day before the experiment and restricted from having food/beverage or being engaged in sporting events one hour before. Prior to commencing the experiment, the subjects reported to the staff in the required clothing, t-shirt and pants (clo = 0.5). In the climatic chamber, the subjects first assumed sedentary activities (reading or light conversation) in the outdoor chamber for 30 min for acclimation to the pre-set thermal condition; they were reminded not to converse on the topic of research. During the acclimation the subjects were periodically examined of their skin site to ensure the absence of visible moisture. The thermal sensation survey and skin physiology evaluation were performed simultaneously at the end of acclimation. The TSV cast and the readings in the physiological properties measured at this time were used as baselines (“0 min”) to which their counterparts secured from later measurements in the indoor chamber were compared. The subjects moved from the outdoor to the indoor chamber immediately after the evaluation, and resumed the activities they were previously engaged in. The parallel evaluation of TSV and physiological properties was conducted at 1, 2, 4, 6, 10, and 20 min after the instantaneous temperature change. The evaluation was conducted intensely in the first 6 min of the adaptive course, as in our preliminary findings the predominant change in SBFC and TEWL in response to temperature step occurred vigorously in minutes after the temperature change. The experiment session ended after all six evaluations were completed. Fig. 1a summarizes the experimental procedures described and the schedules of thermal acclimation, subjective sensation survey, and physiological property measurement; and Fig. 1b demonstrates the measurement of microclimatic variables and t physiological properties in the outdoor chamber.

2.4. Measurement of subjective thermal sensation and skin physiological properties

The subjective thermal sensation in response to step change in temperature was evaluated using a Chinese-based questionnaire resembling the ASHRAE Standard 55 thermal comfort survey [12]. The questionnaire required the subjects to evaluate their subjective sensation towards the thermal environment and grade their perception on a 7-point scale (thermal sensation vote, TSV), with a TSV of 3, 2, 1, 0, -1, -2, or -3 responding to the sensation of “hot”, “warm”, “slightly warm”, “neutral”, “slightly cool”, “cool”, or “cold”, respectively. The “neutral” vote indicates thermal neutrality. The skin physiological properties examined included SBFC, skin moisture, TEWL, and skin temperature. The skin moisture, TEWL, and skin temperature were measured using the Cortex® DermaLab System (Cortex Technology, Hadsund, Denmark) equipped with a TEWL probe (for TEWL measurement) and a flat-head moisture probe (skin moisture). The Moor VMS-LDF tissue blood flow monitor (Moor Instruments, Devon, UK) was used in measuring the SCBF. The readings of skin physiological properties were taken from the dorsal skin of the left forearm located approximately 10 cm from the wrist. The readings of each skin property were sampled consecutively for 10 seconds in each measurement. The dorsal skin of left forearm was selected as the site of skin measurement, as the site of measurement should represent the part of the body that had full exposure to both the thermal environment indoors as well as the ambient environment outdoors, including solar irradiation, when the subjects entered from outdoors into a thermal transient. The volar forearm, hand, and facial skin were not considered, as the volar forearm was less representative of the skin fully exposed to the outdoor environment while the hand and facial skin did not allow for clear observation of SCBF (hand) and TEWL (face) change, respectively.

To confirm that the air temperature and RH in the climatic chamber remained within 5% of the coefficient of variation of the settings, climatic variables were monitored in both the outdoor and indoor chambers throughout each session using CENTER 314

Temperature/Humidity Datalogger (Center Technology Corp., Taipei, Taiwan). The Vair was monitored using DeltaOHM thermo-anemometer HD2103.2 (DeltaOHM, Italy) to ensure a windless condition in the chambers.

2.5. Statistical analysis

The distributions of TSV and examined skin propeties in response to temperature step were partitioned into different gender groups (all subjects, males, and females) and confirmed for normality using the Kolmogorov-Smirnov test [30]. The change of TSV or physiological properties over the adaptive course in response to each temperature step was compared between gender groups using the student's *t*-test. To explore the effect of the magnitude in temperature step on sensational and physiological changes, one-way ANOVA followd by the Scheffe's multiple comparisons procedure were employed to compare the changes in each indicator between temperature steps. The TSV was correlated to each skin physiolgoical property, as partitioned by the gender and the temperature step, to investigate the agreement between TSV and each evaluated property. The signficance of correlation was indicated by the Pearson product-moment correlation coefficient (r). The statistical analysis was conducted using the software SPSS (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Thermal sensation vote

All of the measured data reported in this study and presented in the Results section were obtained under the experimental conditions of RH at 60%, Vair less than 0.2m/s, and clo of 0.5. Fig. 2 shows the change of TSV among the subjects in a thermally neutral environment following the temperature step. As a general trend, the TSV gradually centered on a neutral sensation (TSV = 0) with the adaptive time increasing. However, the pattern by which the TSV changed varied significantly among groups of temperature step ($p < 0.001$; ANOVA), with the most markedly difference observed between the groups of 8^{o}C-gradient temperature down-step and the temperature up-step ($p < 0.001$; Scheffe's multiple comparison).

In the case of air temperature dropping from 32 to 24^{o}C, as shown in Fig. 2a, the sensation of the subjects plummeted initially to levels lower than that observed later when the TSV returned to a steady state, indicating the occurrence of a cold sensation overshot. The overshot was the most significant in the first two minutes of thermal adaptation: the mean TSV of subjects sampled 1 and 2 min post-step change plunged to -0.50 and -0.56, respectively, from the mean TSV of 2.00 observed at 0 min, and was lower than the mean TSV of 0.00 established at the new steady state (20 min). When the incremental change in TSV (ΔTSV) between sampling time points was calculated by extracting the TSV of a preceding time point from the TSV of the next point, a substantial change in TSV was observed in the first min of adaptation (ΔTSV = -2.50) but not in the other acclimation increments (maximal ΔTSV = +0.25). A similar overshot occurred when the subjects experienced a temperature down-step from 28 to 24^{o}C, however at a scale less than the magnitude observed in the 8^{o}C-gradient down-step. The mean TSV sampled at 0, 1, 2, and 20 min was +0.50, -0.25, -0.25, and -0.18, respectively; the ΔTSV of 0 to 1 min post-step change was -0.75 whereas the maximum ΔTSV in the other acclimation increments was 0.06. These observations suggest that the thermal comfort disrupted by temperature transient can be effectively restored as long as the thermal change does not overwhelm the thermoregulatory capacity. Nonetheless, as far as thermal balance is concerned human body is of a significant thermal mass that when challenged by a temperature step the thermoregulation may not rapidly react to. Hence there is often a lag between the occurrence of temperature step and the alleviation of thermal discomfort. As demonstrated in Fig. 2, the level of sensation change and the period required to establish a new steady state were strongly influenced by the magnitude of the temperature step.

In comparison, when the subjects moved into the thermally neutral zone from a colder thermal environment, i.e., a temperature ramp from 20 to 24^{o}C, the TSV did not overshoot towards the warmer sensation in the initial acclimation period as it did following temperature down-steps. The mean TSV sampled at 0, 1, 2, and 20 min was -2.06, -0.25, -0.19, and -0.06, showing a stable rise of the sensation to a steady state. The gender difference was not statistically significant in the TSV change or in the incremental ΔTSV over the adaptive course ($p > 0.05$; student's *t*-test).

3.2. Skin capillary blood flow

The vasodilation or vasoconstriction of blood vessels on the skin surface occurs prior to sweating or muscle contraction/shivering in response to the alteration in thermal environment. Fig. 3 shows the change in the SBFC of the subjects in the indoor chamber following a temperature step. The SBFC change varied significantly among groups of temperature step ($p < 0.001$; ANOVA). The perfusion rate of the capillary blood was higher when the subjects moved into the thermally neutral zone from a warmer environment than from a colder one; the SCBF at 0 min was 14.57, 11.14, and 7.46 perfusion unit (PU) for the groups of 8^{o}C-gradient down-step, 4^{o}C-gradient down-step, and 4^{o}C-gradient up-step, respectively. These were the SCBF levels indicative of the heat transfer status immediately prior to the temperature change—the higher the initial air temperature, the greater the SCBF level. When the air temperature stepped down from 32 to 24^{o}C, in response to the requirement of heat conservation the SCBF plummeted initially and then slowly reached a steady state of 8.42 PU at 20 min. The overshot at 1 min and the subsequent return in the next 5 min before reaching a steady level resembled the cold sensation overshot observed in the TSV change. This trend, however, was not clear in the temperature step of 28 to 24^{o}C; the lack of overshot was probably an indication of insufficient requirement in heat transfer when the temperature down-step was less than 8^{o}C. The SCBF reached 8.42 (8^{o}C-gradient temperature down-step), 9.34 (4^{o}C-gradient down-step), and 6.46 PU (up-step) at 20 min, rendering a reduction of 6.15, 1.80, and 1.00 PU in SBCF, respectively, from their initial levels (0 min). However, the reduction was statistically significant only when the temperature step reached 8^{o}C ($p < 0.001$; paired *t*-test), attesting to the earlier inference that neither the requirement of heat dissipation nor of conservation was sufficiently significant when the temperature step was limited to ±4^{o}C.

The SCBF change over the course of adaptation was significantly different between males and females when the temperature stepped down from 32 to 24^{o}C ($p < 0.001$; student's *t*-test) and up from 20 to 24^{o}C ($p < 0.001$), but less different in the case of temperature down-step from 28 to 24^{o}C ($p = 0.089$). In both cases where a significant difference between genders was found, the mean SCBF levels for males at all time of acclimation were greater than their counterparts for females, suggesting a greater capacity in the metabolic heat generation of the males than that of females recruited in the study. The mean SCBF levels in both sexes were similar when the new steady state was reached in the group of temperature down-step from 32 to 24^{o}C (PU = 8.94 and 7.91 at 20 min for males and females, respectively);

however such a similarity lessened, if present at all, in the group of up-step (PU = 7.52 for males and 5.39 for females). It appeared that the metabolic heat load of females in this study was generally less than that of males. Subsequently, when the temperature up-step was only 4°C, the females were not prompted to release excess body heat as the males did and as a result the capillary vessels remained largely constricted during thermoregulation.

3.3. Skin moisture

Fig. 4 shows the change of skin moisture at 24°C after an instantaneous temperature drop from 32/28°C or rise from 20°C. The difference in the skin moisture change among groups of temperature step was significant ($p = 0.001$; ANOVA) except between the temperature down-step from 28 to 24°C and the up-step ($p > 0.05$; Scheffe's multiple comparison). Compared to the remarkable change in SCBF observed in the temperature step of 8°C, the distinct reduction of skin moisture following the same magnitude of temperature step suggests that, when required in heat transfer, the change in skin moisture becomes apparent only when the requirement of heat transfer is not met with its thermoregulatory precursor, the dilation or constriction of blood vessels. Further support of this suggestion was observed in the initial decrease in skin moisture during acclimation: when the temperature stepped down from 32°C, the mean skin moisture of all subjects declined from 636 μS (0 min) to a steady state of 168 µS (10 min) in 10 min, whereas the change in response to a down-step from 28°C was only minor, decreasing from 178 µS (0 min) to 120 µS in 1 min. The heat transfer requirement in the temperature down-step from 28 to 24°C was clearly insufficient to drive a significant change in either SCBF or skin moisture. The overshot seen in the SCBF change following a temperature down-step from 32 to 24°C was not observed in the skin moisture, suggesting that being a downstream thermoregulatory event the skin moisture was less influenced by the surge of heat transfer if the surge was partially buffered during SCBF change.

Between genders, the skin moisture change triggered by temperature step was only significant in the temperature down-step from 32 to 24°C ($p = 0.001$; student's *t*-test). The mean skin moisture levels for males in this case at all sampling times were higher than their counterparts for females, and the acclimation period for males was also longer (10 min) than that of females (1 min), again supporting the inference that the male subjects recruited in this study in general had a greater metabolic load.

3.4. Transepidermal water loss

Describing the rate of invisible formation of water vapor on the skin surface, a change in TEWL signifies the beginning of the thermoregulatory stage in which the heat is directly transferred between the body and the environment, if the requirement of heat transfer is not satisfied by the change in SCBF and skin hydration. Fig. 5 shows the immediate change of TEWL in thermal neutrality after a temperature step. The difference in the TEWL change was statistically significant between all groups of temperature step (*p* < 0.001; ANOVA and Scheffe's multiple comparison).

Tracking the change in SCBF and skin moisture, the change of TEWL over the adaptive course was the most pronounced when the temperature stepped down from 32 to 24^{o}C, and the TEWL reduction was the most significant in the initial period of acclimation. As observed in the 8^{o}C-gradient down-step group, the TEWL first decreased substantially (23.34 g/m^{2}/hr at 0 min to 14.01 g/m^{2}/hr at 1 min), but then slowly surged to a peak at 6 min (15.64 g/m^{2}/hr) before declined again to a stable level (10.00 g/m^{2}/hr). The appearance of the TEWL peak at 6 min was also observed in the other two temperature step groups, but at a lesser extent. This finding suggests that the TEWL responds to thermoregulatory requirement arising from a temperature step in two stages. First the TEWL answered the call of thermoregulation in a swift manner similar to those observed in the SCBF and skin moisture. However, the thermal shock brought upon the body by temperature step in the initial acclimation period might be overly regulated. As a result, a feedback adjustment would occur later as the acclimation continued towards a thermal balance. A similar phenomenon was also noticed in all temperature-step groups for the SBFC and in the 4^{o}C-gradient down-step/up-step groups for the skin moisture, but the trend was not statistically clear. While the TEWL surge in the case of temperature up-step might be attributed to a thermoregulatory attempt to release excess body heat produced when the body acclimated to a warmer environment, the surge in the down-step cases suggested a thermal balance to the heat actively conserved during the initial period of temperature drop by means of minor dissipation as the acclimation moved on. The TEWL change was significantly different between males and females at all temperature steps (*p* < 0.001; student's *t*-test). In all cases, the mean TEWL levels for males were greater than their counterparts for females. The surge of TEWL at 6 min was more pronounced in males.

3.5. Skin temperature

Fig. 6 shows the change of skin temperature at 24°C following the step change in air temperature. The difference in the change of skin temperature among temperature steps was significant (*p* < 0.001; ANOVA), except between the two temperature down-step groups (*p* > 0.05; Scheffe's multiple comparison). In both down-step situations, the skin temperature plunged in the first min of acclimation, and reached a new steady state (29.82-30.59°C) in approximately 10 min. Following the temperature up-step, the skin temperature also adjusted and reached a new steady state (28.85°C) in 10 min, however at a slower rate. Another difference between the temperature up- vs. down-step existed in the appearance of an overshot in the skin temperature; the overshot was present in cases of temperature down-steps, but not in the case of up-step. Compared to the overshot observed in SCBF, the skin temperature overshot was more pronounced and occurred in both temperature down-steps. The skin temperature change in response to temperature step was statistically significant between genders in the cases of temperature down-step from 28 to 24^{o}C ($p = 0.028$; student's t-test) and of up-step ($p < 0.001$), but not in the case of down-step from 32 to 24^{o}C ($p = 0.786$). For the 4^{o}C-gradient temperature down-step, the mean skin temperatures for females were found to be greater than their counterparts for males.

4. Discussion

4.1. Correlation between subjective sensation and skin physiological changes

In this study, the subjective sensation of thermal comfort was found to quickly reach neutrality in the new thermal environment after a temperature step; however the thermoregulation manifested as change in skin properties required a longer period to complete. In thermoregulation, when a change in the thermal status of the environment registers with the thermoreceptors in the skin, the skin temperature functions as a sensor and delivers the information to the thermoregulatory center. The gradient between the skin and the core temperature initiates the process of thermoregulation and dictates the level of heat transfer required between the body and the environment [15,31]. As a leading event in thermoregulation, the SCBF responds swiftly to the thermal environmental change. The fast-reacting characteristic of skin temperature and SCBF was evidenced in this study by the synchronous appearance of cold sensation overshot in the change of TSV, SCBF, and skin temperature immediately after the temperature down-step of 8^oC began. In contrast, when the temperature transient occurred the TEWL first changed in accordance with the alteration in SCBF and skin moisture, but as acclimation continued the TEWL adjusted again likely to feedback on the initial regulation before establishing thermal balance with the environment. The two-stage adjustment in TEWL as observed demonstrates that the thermoregulation in response to temperature step is a slow-evolving process compared to the adaptation of thermal sensation. Being a stage of thermoregulation directing the heat exchange between the body and the environment, the change in TEWL occurs after those in SCBF and skin moisture, serving to fine-tuning the thermoregulatory effort before thermal balance is reached. A similar observation was made by Chen and Wu [29] in their experiment studying the change in skin moisture and TEWL in response to microclimatic alteration, in which the onset of skin moisture change was found to precede the beginning of TEWL change when dissipation of excess body heat was required. McLellan et al. [19] investigated the change in skin moisture at different body parts of young and elderly subjects acclimated to different air temperatures, and reported that the rise in skin moisture in young subjects with increasing globe temperature was inversely correlated to the change in skin temperature. The increased heat storage resulting from hydration of epidermal and subcutaneous layers of the skin appeared to slow down the heat dissipation investigated in MeLellan et al., suggesting a feedback of skin moisture on the dynamic balance of skin temperature with the thermal environment when a steady state was re-established.

The difference in the course of sensational adaptation vs. of thermoregulation as discussed warrants an analysis on the level of agreement between the TSV and the skin physiology examined in response to a instantaneous temperature change. Fig. 7 shows the distributions of TSV against skin properties, classified by gender, and Table 2 includes the correlation coefficients determined for each distributions, as sorted by temperature step as well as by gender. Among the physiological properties examined, the most robust correlation with TSV was found in skin temperature, reflecting that the sensor characteristic of skin temperature was in sync with the subjective perception of thermal status. The significant correlation between TSV and skin temperature also corresponds to the overshot of these two indicators during a temperature down-step, most noticeably in the 32-to-24^{o}C change. Although an overshot similar to that in TSV was observed in SCBF, the SCBF was the least correlated to the TSV, possibly attributed to the continuous adjustment of the SCBF after the overshot and before reaching the new steady state (Fig. 3). As the intermediate stages in thermoregulation, the skin moisture and TEWL were correlated moderately to the TSV when samples were pooled from all temperature-step groups for all subjects. The correlation between TEWL and TSV was less than that between skin moisture and TSV, again likely a result of the unique surge in TEWL at around 6 min of acclimation, distinguishing the adaptive change of TEWL from that of TSV.

As far as the effect of temperature step was concerned, the correlation between TSV and skin properties was greater in the temperature down-step and when the down-step was significant (i.e., 8^{o}C). The correlation between TSV and physiological properties was the most pronounced when the air temperature stepped down from 32 to 24^{o}C, except in the case for SCBF, compared to those in the other groups of temperature step. The correlation of the skin moisture and TEWL with the TSV provides an illustration on this effect of temperature step. As our results show (Figs. 4 and 5), the changes in skin moisture and TEWL were significant at the temperature down-step of 32 to 24^{o}C, but less at the down-step of 28 to 24^{o}C and the up-step of 20 to 24^{o}C. This finding suggested that the heat exchange requirement upon a temperature step of 4^{o}C was insufficient to drive thermoregulation into the stage of heat transfer via the change in skin moisture and TEWL. However, the TSV of the subjects was responsive to the same level of microclimatic change, particularly in the case of temperature up-step from 20 to 24^{o}C. As a consequently, both the skin moisture and TEWL were better correlated with the TSV at the 8^{o}C-gradient temperature step, but poorly at the 4^{o}C-gradient temperature steps.

These findings did not exclude the possibility that the TSV might be significantly correlated to the skin properties when responding to a temperature up-step. Rather, it suggested that a greater range of temperature up-step than the level applied in this study might be required to visualize the thermoregulation involved in acclimation towards a warmer environment. As demonstrated, when intended as an alternative indicator of thermal strain due to temperature step, the skin physiology may be reasonably applied at a temperature step of 8^{o}C or greater. The lack of significant change in skin properties at a temperature step of 4^{o}C or less suggests that thermoregulatory burden may be adequately reduced when the temperature step in a thermal transition zone does not exceed this level.

4.2. Role of gender in thermal sensation adaptation and thermoregulation

Several studies investigated the gender as a factor in thermal comfort in response to change in thermal environment among Taiwanese populations [32-34]. Hwang et al. [32,33] studied the thermal comfort requirements of the university students in classrooms and of the patients in hospital wards; in neither case the gender was identified as a significant factor. Hwang and Chen [34] evaluated the thermal sensation of elderly males vs. females at home and their strategies of thermal adaptation. The difference in the neutral temperatures identified for males and females was less than 0.5^{o}C, in both the summer and the winter, again excluding the gender as an influential factor. Similarly, in this current study the change in TSV in response to temperature step between genders was not found to be statistically different.

However, significant difference was observed between the genders in the occurrence of thermoregulatory events as well as in the magnitude of response in these events. As reported earlier, the levels of SCBF, skin moisture, and TEWL were significantly higher for males than for females when reaching the new steady state, particularly when the air temperature dropped from 32 to 24^{o}C, possibly as a result of greater metabolic load of males as implied in their BMI levels. The lack of gender effect in the adaptation of thermal sensation may be partly explained by the limitation inherent in the thermal comfort survey—thermal comfort is essentially a intuitive recognition of the thermal status and thus subject to significant inter-individual variation. When provoked with a transient temperature, individual variation may become sufficiently significant to mask over the influence of gender on the thermal perception expressed as TSV. When the correlations of TSV with skin properties were classified by gender (Table 2), the TSV was less correlated to the skin moisture and TEWL and more to the SCBF and skin temperature for females than their counterparts for males. The higher association between TSV and skin moisture/TEWL for males was largely attributed to an elevation in these two skin properties of males compared to the levels of females when air temperature dropped from 32 to 24^{o}C (Figs. 4, 5, and 7). This finding indicates: the thermoregulation involved in the heat exchange between the skin and the environment, as manifested in the change of skin moisture and TEWL, was more vigorous for male participants of the study. In contrast, the primary mechanism of heat transfer for females appeared to be through the SBFC adjustment.

Of all the physiological properties evaluated, the skin temperature most consistently corresponded to the subjective thermal sensation regardless of gender. The sensor-resembling and fast-reacting characteristics of skin temperature responding to microclimatic change render it a unique property that possibly associates more with reflecting the environmental change than indicating the corresponding thermoregulatory adjustment. This is evidenced by the significant correlation between the TSV and skin temperature at all temperature steps. In addition, as the changes in SCBF, skin moisture, and TEWL of males responded vigorously at levels greater than their counterparts of females in the 32-to-24^{o}C temperature down-step (Figs. 3-5), a similar trend of change in skin temperature would be expected, if the skin temperature was indicative of the thermoregulatory adjustment in progress. However, similar to the lack of gender difference in the TSV change in response to the 8^{o}C-gradient temperature down-step (Fig. 2), a statistically significant difference between genders was not observed for skin temperature change in response to the same magnitude of temperature down-step. Thus, it is unclear if the gender difference in skin temperature observed in the 4^{o}C-gradient temperature down-step as reported from statistical analysis was authentic. Another confounding factor that might influence the distribution of skin temperature of the subjects other than the microclimatic variables was the basal metabolism. The temporal shift in the metabolic rate of the subjects in response to the physical status of individuals and their interaction with the ambient environment could introduce interference to the physiological evaluation. Considering the gender-specific difference observed in the other skin properties, the observation here also attests to the limitation of the skin temperature as a means of exploring thermoregulatory details involved in thermal adaptation.

5. Conclusions

This study investigated the change of subjective thermal sensation and corresponding thermoregulation involved in acclimation to temperature step occurring in a thermal transition zone. All of the measured data reported were obtained under the experimental conditions of RH at 60%, Vair less than 0.2m/s, and clo of 0.5. The following conclusions were derived:

(1) The change in thermal sensation, expressed in TSV, was most vigorous in the first min of acclimation; a cold sensation overshot was observed, most noticeably when the temperature instantaneously dropped from 32 to 24^{o}C.

(2) Among the selected skin physiological properties, the initial change of skin temperature in response to temperature down-step tracked the cold sensation overshot observed in TSV.

(3) The TEWL decreased rapidly in the initial stage of adaptation to temperature down-step, but surged again as the acclimation continued, resulting in a divergence between the courses of sensational adaptation and thermoregulation.

(4) TSV was best correlated with skin temperature and moderately with skin moisture and TEWL; the correlation between TSV and skin properties was the most pronounced in the temperature down-step from 32 to 24^{o}C.

(5) Gender was an influential factor in thermoregulation but not in thermal sensation change. The levels of SCBF, skin moisture, and TEWL were significantly higher for males than for females, particularly in temperature down-step from 32 to 24^{o}C.

(6) The lack of significant physiological changes at a temperature step of 4^{o}C or less suggests that thermoregulatory burden in a thermal transient may be adequately controlled when the temperature step does not exceed this level.

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decision to submit the paper for publication.

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Figure Captions

Fig. 1. (a) Experimental design using twin climatic chambers simulating entry from an outdoor environment ("outdoor chamber") into a temperature-controlled building ("indoor chamber") and schedule of evaluating thermal sensation vote (TSV) and skin physiology; (b) measurement of microclimatic variables and physiological properties in the outdoor chamber.

Fig. 2. Change in thermal sensation vote (TSV) of all, male, and female subjects over time in response to temperature steps from (a) 32°C, (b) 28°C, and (c) 20°C to 24°C. The symbol and error bar shown at each time point are the mean and standard deviation of the distributed data, respectively.

Fig. 3. Change in skin capillary blood flow (SCBF) of all, male, and female subjects over time in response to temperature steps from (a) 32°C, (b) 28°C, and (c) 20°C to 24°C. PU = perfusion unit. Statistical measures are the same as for Fig. 2.

Fig. 4. Change in skin moisture over time of all, male, and female subjects in response to temperature steps from (a) 32°C, (b) 28°C, and (c) 20°C to 24°C. Statistical measures are the same as for Fig. 2.

Fig. 5. Change in transepidermal water loss (TEWL) of all, male, and female subjects over time in response to temperature steps from (a) 32°C, (b) 28°C, and (c) 20°C to 24°C. Statistical measures are the same as for Fig. 2.

Fig. 6. Change in skin temperature of all, male, and female subjects over time in response to temperature steps from (a) 32^{o}C, (b) 28^{o}C, and (c) 20^{o}C to 24^{o}C. Statistical measures are the same as for Fig. 2.

Fig. 7. Distribution of thermal sensation vote (TSV) by (a) skin capillary blood flow (SCBF), (b) skin moisture, (c) transepidermal water loss (TEWL), and (d) skin temperature under influence of temperature step.

Table Titles

Table 1 Anthropometric data of subjects participating in the study

Table 2 Pearson's coefficient of correlation between thermal sensation vote and skin physiological property determined for different temperature steps and genders[a]. The evaluated physiological properties included skin capillary blood flow (SCBF), skin moisture, transepidermal water loss (TEWL), and skin temperature

Table 1

Anthropometric data of subjects participating in the study

	Male	Female	All
Number (n)	8	8	16
Age (year)	21.0 ± 1.3	20.6 ± 0.7	20.8 ± 1.1
Height (cm)	173.4 ± 6.0	157.5 ± 5.5	165.4 ± 9.9
Weight (kg)	65.3 ± 10.6	46.3 ± 5.5	55.8 ± 12.8
BMI (kg/m^2)	21.7 ± 3.1	18.6 ± 1.7	20.2 ± 2.9

Table 2

Pearson's coefficient of correlation between thermal sensation vote and skin physiological property determined for different temperature steps and genders[a]. The evaluated physiological properties included skin capillary blood flow (SCBF), skin moisture, transepidermal water loss (TEWL), and skin temperature

	SCBF	**Skin moisture**	**TEWL**	**Skin temperature**
Overall	0.19**	0.43**	0.34**	0.49**
Temperature step				
32°C → 24°C	0.12	0.54**	0.42**	0.60**
28°C → 24°C	0.22*	0.09	0.07	0.48**
20°C → 24°C	0.10	0.19	0.02	0.30**
Gender				
Male	0.17*	0.53**	0.43**	0.46**
Female	0.19*	0.38**	0.21**	0.51**

[a] Statistical power of analysis determined for each correlation; asterisks * and ** denoting $p < 0.05$ and $p < 0.01$, respectively.

Figure 1

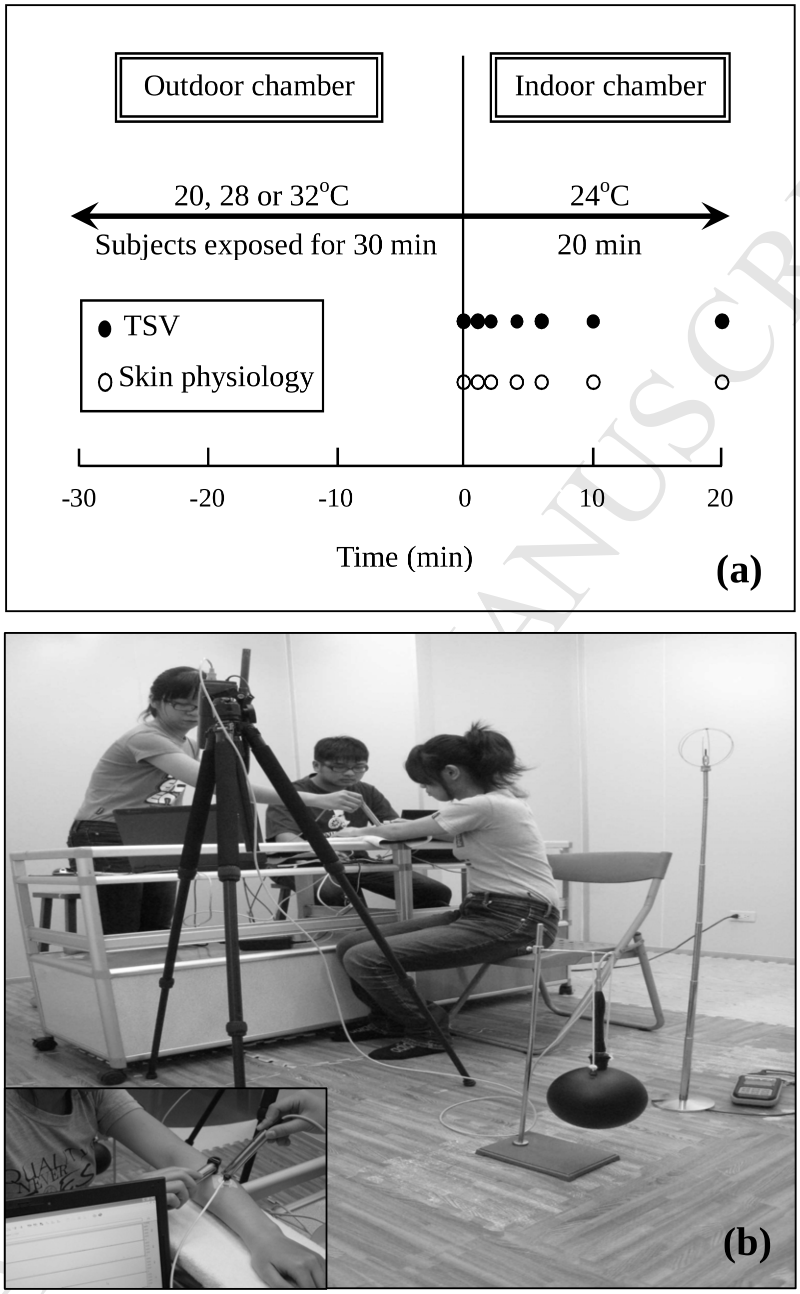

Outdoor chamber
Indoor chamber
20, 28 or 32°C
24°C
Subjects exposed for 30 min
20 min
● TSV
○ Skin physiology
-30
-20
-10
0
10
20
Time (min)
(a)
(b)

Figure 2

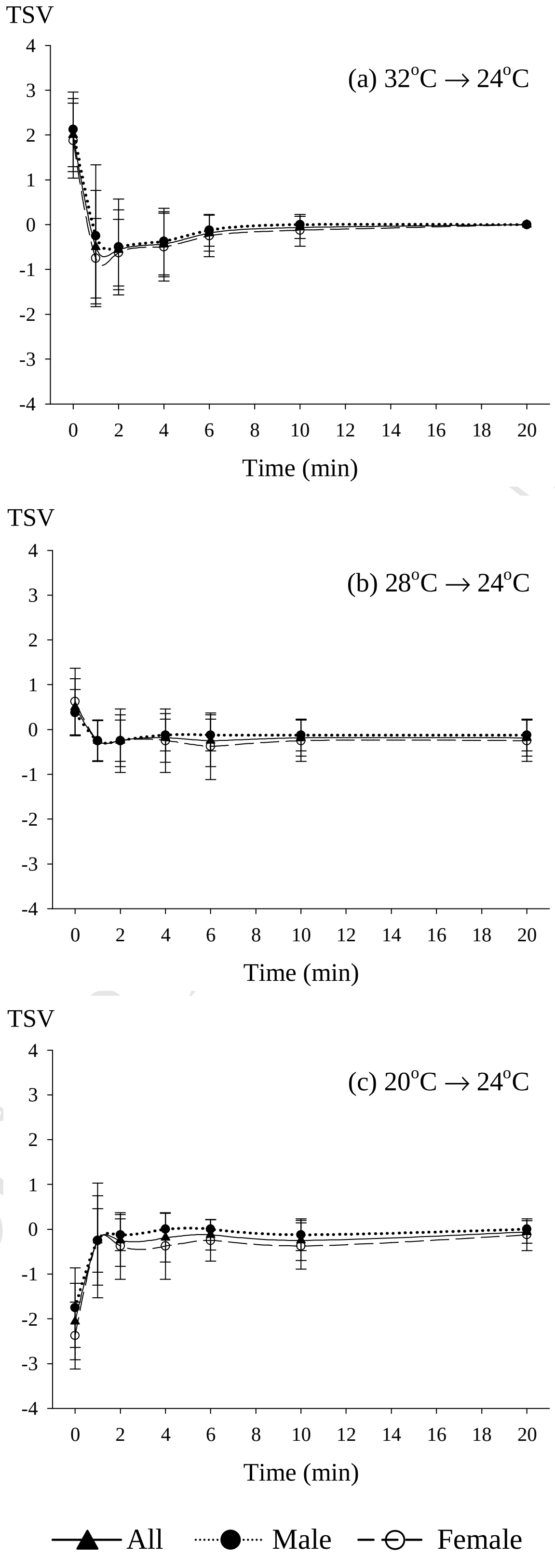

TSV
4
3
2
1
0
-1
-2
-3
-4
(a) 32°C → 24°C
0
2
4
6
8
10
12
14
16
18
20
Time (min)
TSV
4
3
2
1
0
-1
-2
-3
-4
(b) 28°C → 24°C
0
2
4
6
8
10
12
14
16
18
20
Time (min)
TSV
4
3
2
1
0
-1
-2
-3
-4
(c) 20°C → 24°C
0
2
4
6
8
10
12
14
16
18
20
Time (min)
All
Male
Female

Figure 3

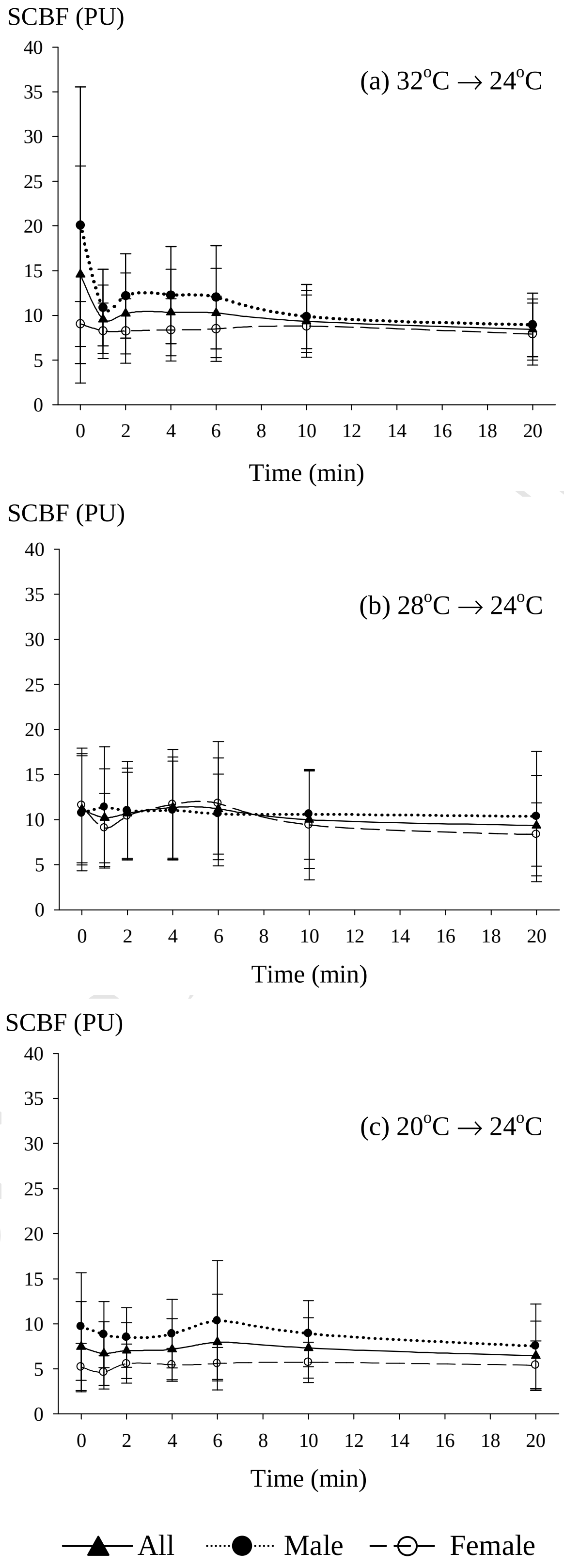

SCBF (PU)
40
35
30
25
20
15
10
5
0
(a) 32°C → 24°C
0 2 4 6 8 10 12 14 16 18 20
Time (min)
SCBF (PU)
(b) 28°C → 24°C
Time (min)
SCBF (PU)
(c) 20°C → 24°C
Time (min)
All
Male
Female

Figure 4

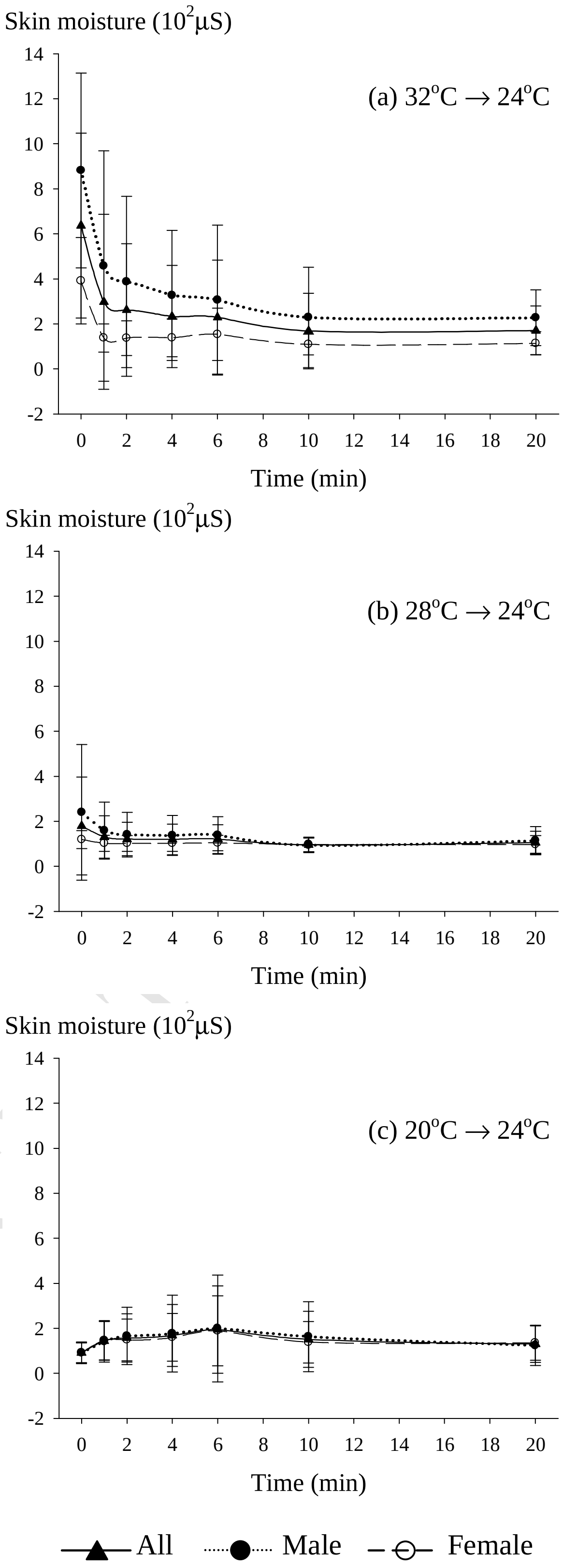

Skin moisture (10²μS)
14
12
10
8
6
4
2
0
-2
(a) 32°C → 24°C
0
2
4
6
8
10
12
14
16
18
20
Time (min)
Skin moisture (10²μS)
(b) 28°C → 24°C
Time (min)
Skin moisture (10²μS)
(c) 20°C → 24°C
Time (min)
All
Male
Female

Figure 5

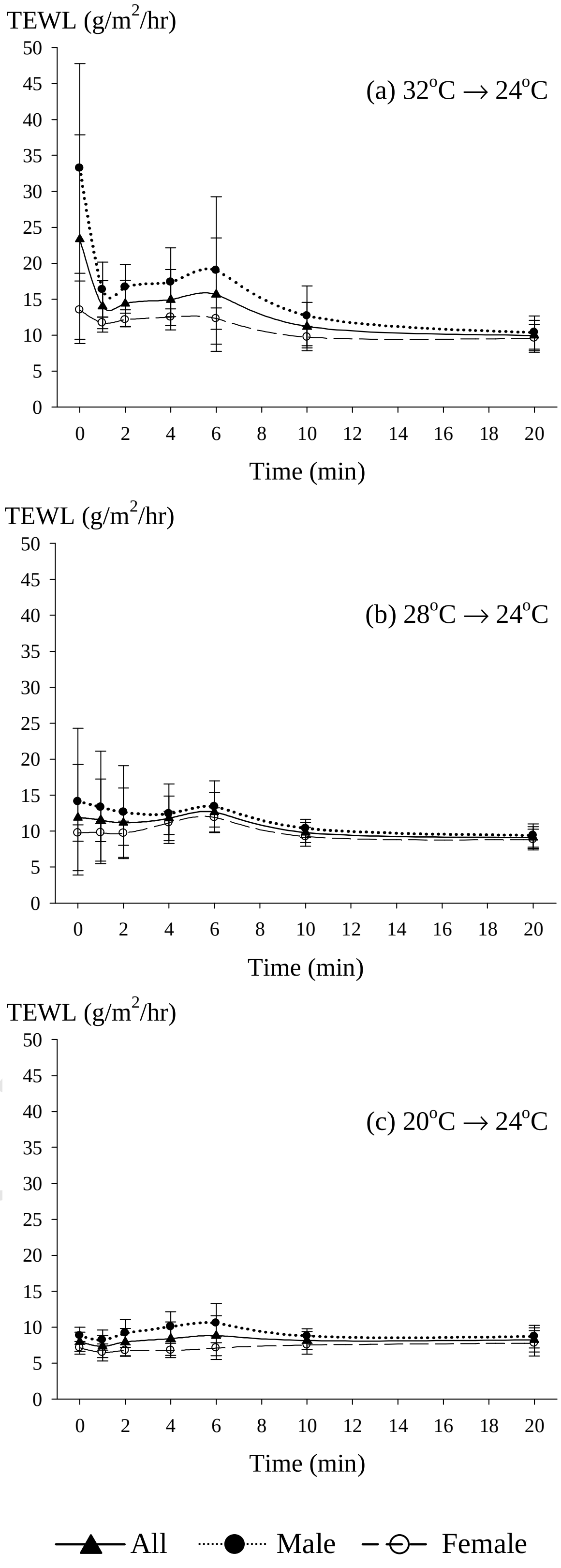

TEWL (g/m²/hr)
50
45
40
35
30
25
20
15
10
5
0
(a) 32°C → 24°C
0
2
4
6
8
10
12
14
16
18
20
Time (min)
TEWL (g/m²/hr)
(b) 28°C → 24°C
Time (min)
TEWL (g/m²/hr)
(c) 20°C → 24°C
Time (min)
All
Male
Female

Figure 6

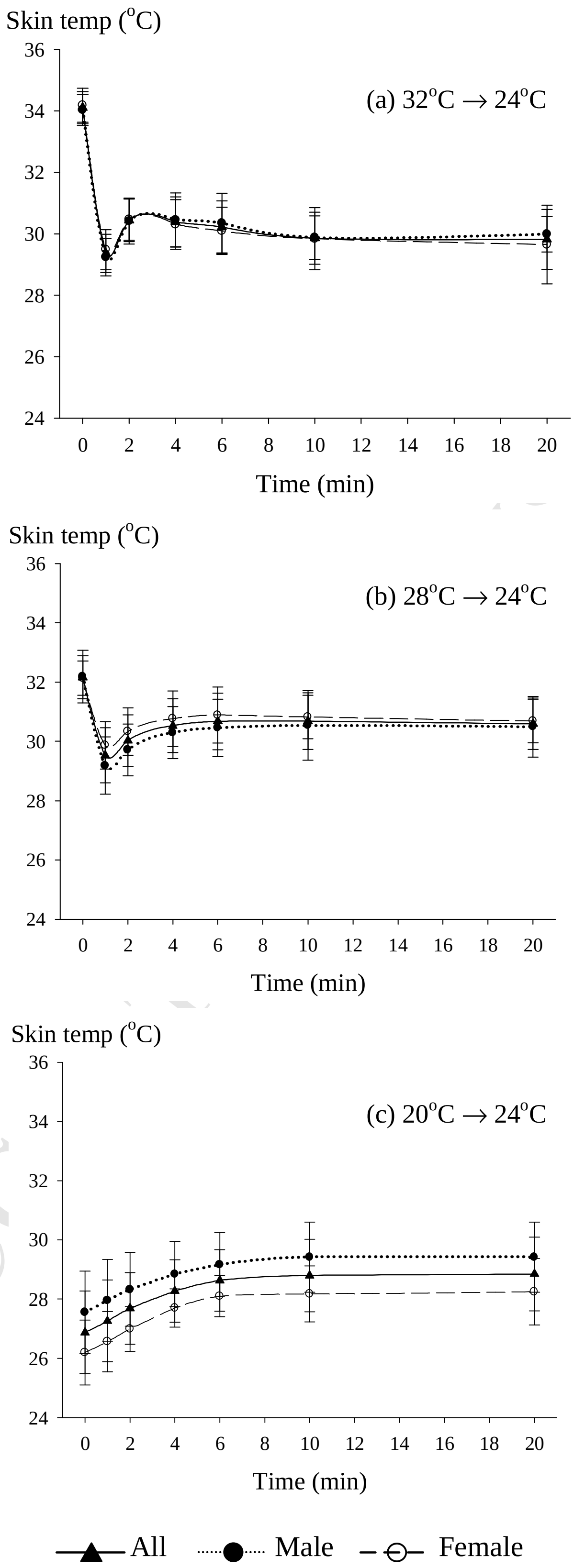
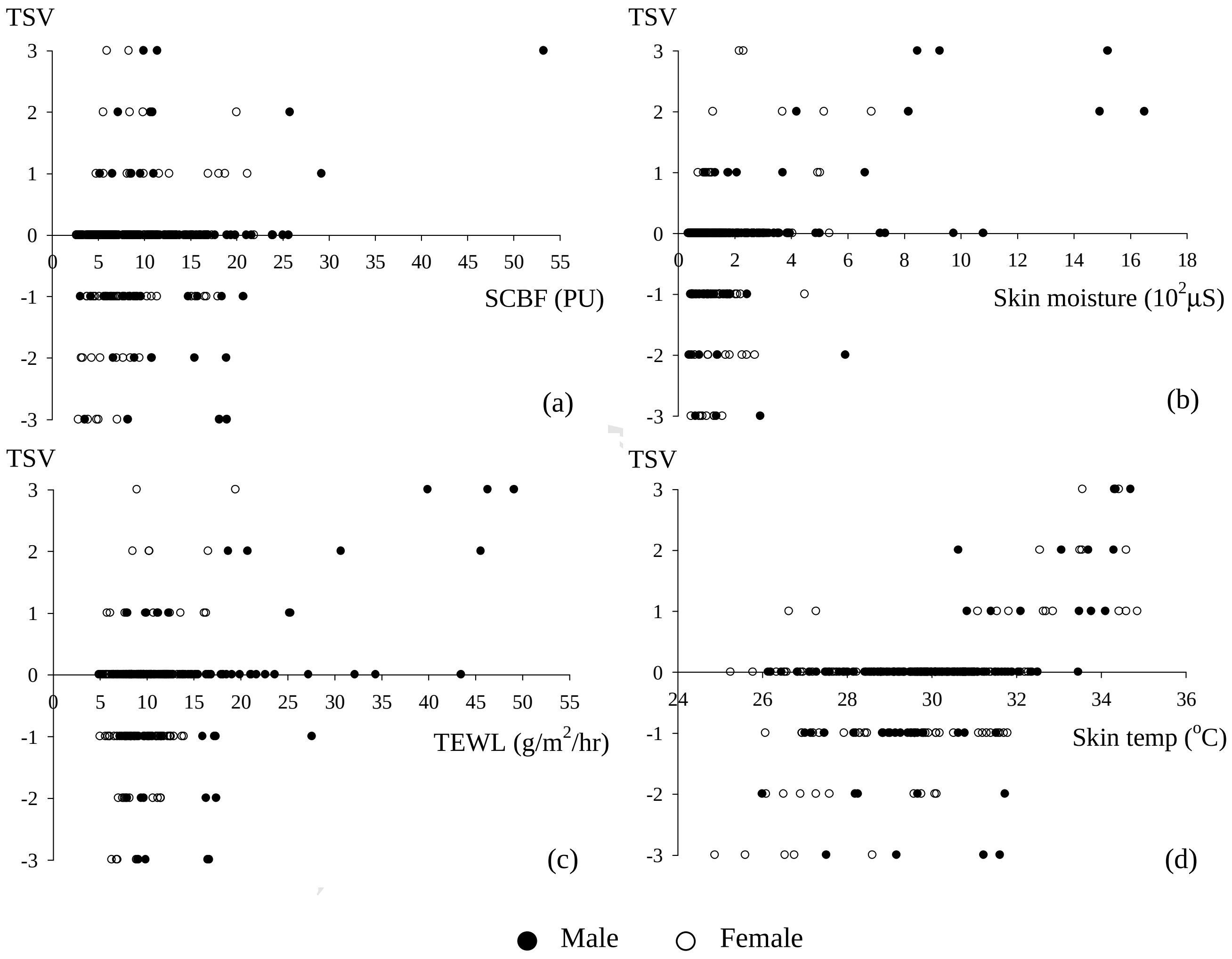

Skin temp (°C)
36
34
32
30
28
26
24
(a) 32°C → 24°C
0
2
4
6
8
10
12
14
16
18
20
Time (min)
Skin temp (°C)
(b) 28°C → 24°C
Time (min)
Skin temp (°C)
(c) 20°C → 24°C
Time (min)
All
Male
Female

Figure 7


TSV
3
2
1
0
-1
-2
-3
0 5 10 15 20 25 30 35 40 45 50 55
SCBF (PU)
(a)
TSV
0 2 4 6 8 10 12 14 16 18
Skin moisture ($10^2\mu S$)
(b)
TSV
0 5 10 15 20 25 30 35 40 45 50 55
TEWL ($g/m^2/hr$)
(c)
TSV
24 26 28 30 32 34 36
Skin temp (^oC)
(d)
● Male
○ Female