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Correlation analysis of thermal comfort and physiological responses under different microclimates of urban park

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ABSTRACT

Rapid urbanization has brought a range of urban environmental problems that could be harmful to human thermal comfort and health. Urban parks can improve outdoor thermal comfort significantly because of its cooling island effect. However, outdoor thermal comfort is difficult to predict because of its complex nature and there was rare research focused on human physiological thermal responses in different green spaces of urban parks. In this study, thermal comfort of 52 participants were evaluated based on questionnaire survey and physiological parameters measurements including skin temperature (SKT), oxygen saturation (SaO2), heart rate (HR), heart rate variability (HRV) under different green spaces in parks, simultaneously with microclimate measurements. According to the regression analysis, physiological parameters were found having high accuracy in predicting human outdoor thermal comfort, with R^2 were 0.803 for SKT, 0.830 for HRV, 0.767 for HR, 0.711 for SaO2 respectively. Results demonstrated that these four physiological parameters were sensitive to microclimate changes and human outdoor comfort thermal state can be captured by monitoring them with reasonable accuracy. This research can provide reference to evaluate outdoor thermal comfort by incorporating the physiological parameters, which can also provide a design basis for creating thermal comfortable outdoor spaces in urban parks.

Nomenclature

ASV	Air temperature sensation vote
BMI	Body mass index, kg/m^2
HR	Heart rate, bmp
HRV	Heart rate variability
HSV	Humidity sensation vote
LF/HF	low frequency band/High frequency band
PET	Physiological equivalent temperature, °C
Rh	Relative humidity, %
RSV	Solar radiation sensation vote
SaO2	Oxygen saturation, %

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SKT	Skin temperature, °C
Sr	Solar radiation, W/m²
SVF	Sky view factor, %
$T_{forehead}$	Temperature of the forehead, °C
T_{chest}	Temperature of the chest, °C
T_{back}	Temperature of the back, °C
$T_{thighs\ arms}$	Temperature of the thighs arms, °C
$T_{thighs\ legs}$	Temperature of the thighs legs, °C
Ta	Air temperature, °C
TCV	Thermal comfort vote
TSV	Thermal sensation vote
UTCL	Universal thermal comfort index, °C
Ws	Wind speed, m/s
WSV	Wind speed sensation vote

1. Introduction

Since 1950, rapid urbanization has taken place around the world. According to the United Nations, 56.6% (2021) of the world's population now live in urban areas, and the number is expected to reach 68% by 2050 [1]. The growth of urban population brings about a series of urban environmental problems, which affect the health and quality of citizens' life seriously. As an important part of urban green space system and the primary green space for outdoor activities, urban parks play an important role in public health. However, global warming can deteriorate thermal comfort of urban spaces, which can influence the usage of parks especially in summer. It is very important to figure out ways to improve thermal comfort in order to mitigate and adapt to climate change. First and foremost is the accurate evaluation of human thermal comfort, however, it is difficult to evaluate outdoor thermal comfort because of its dynamic and complex nature.

Human thermal comfort is clearly defined as "That condition of mind in which satisfaction is expressed with the thermal environment" in the 55th ASHRAE Standard, that is, the state of consciousness that the human body feels satisfied with the thermal environment [2]. This definition is considered appropriate and commonly applied worldwide [3]. As the urban environment deteriorates, there is increasing interest in outdoor thermal comfort and health research. After a systematic review, we found the evaluation of outdoor thermal comfort focuses on physical, psychological, physiological and behavioral aspects in the current research.

Physical environment determines the energy exchange between human body and surrounding environment to a large degree [4]. The physical factors affecting outdoor thermal comfort mainly include microclimatic factors such as air temperature (Ta), relative humidity (Rh) and wind speed (Ws), solar radiation (Sr). Among the above four microclimate parameters, many studies have proved that air temperature was the most important parameter affecting outdoor thermal comfort [5–7]. However, it is difficult for us to adjust the Ta directly when improve the thermal comfort of urban outdoor spaces. The general approach is to control the level of Sr or Ws. For example, in a study of Guelma city, Algeria found that increasing the vegetation ratio and linear water bodies was the best solution to improve outdoor thermal comfort [8].

In the meantime, the evaluation indexes of human thermal comfort based on microclimate parameters have been developed, such

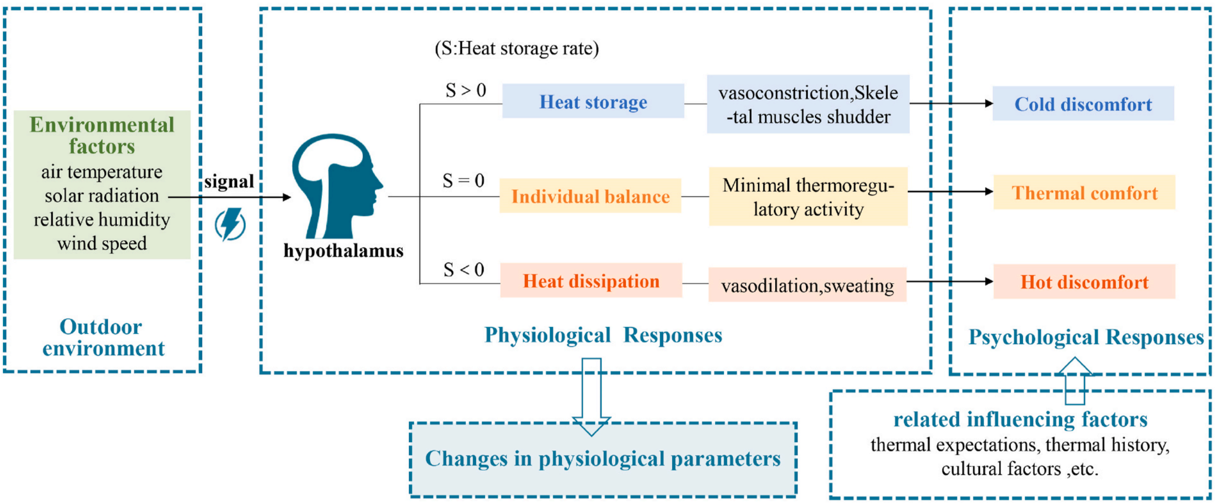


Fig. 1. Thermoregulation activity process.

as universal thermal comfort index (UTCI) [9], physiological equivalent temperature (PET) [10], which have been widely used in outdoor thermal comfort evaluation in various climate areas.

In the majority of studies about human thermal comfort evaluation, questionnaires or interviews were used frequently, with relevant evaluation indicators including thermal sensation vote (TSV), thermal comfort vote (TCV), air temperature sensation vote (ASV), humidity sensation vote (HSV), wind speed sensation vote (WSV), solar radiation sensation vote (RSV). This kind of evaluation method is an essential method for the study of human thermal comfort since it is relatively simple to operate and can understand the thermal comfort directly. However, this method relies on the participant's subjective judgment, which often causes inaccuracy of evaluation results [11].

The connection between physiological factors and outdoor thermal comfort begins with the heat exchange between the human body and the surrounding environment. Normally the human body can utilize evaporating sweat, convection, heat conduction and other ways to dissipate heat and storage heat, so as to maintain a thermal balance with the surrounding environment, and this thermoregulatory activity will cause corresponding changes in the human body's relevant physiological parameters [12]. Therefore, relevant physiological parameters can be used as an objective evaluation index of human thermal comfort although human thermal comfort is a subjective feeling, in view of the correlation between physiological parameters and thermal comfort. (Fig. 1).

Physiological parameters can reflect the degree of human thermal comfort objectively. Therefore, combining objective physiological evaluation and subjective questionnaire evaluation can improve the reliability of the results greatly. In recent years, researchers have begun to establish a link between physiological parameters and thermal comfort, in order to explore the mechanism of human thermal comfort from the physiological point of view. However, because the measurement of physiological parameters is cumbersome, most of the current outdoor thermal comfort studies conducted subjective evaluations, and only a few of them combined physiological parameters to evaluation of human thermal comfort. Among physiological parameters related to thermal comfort, SKT is the most frequently studied parameter. Many studies have found that SKT was sensitive to changes in environmental temperature and correlated with TSV and TCV highly [13]. Evaluation of outdoor thermal comfort depended on SKT largely according to previous researches [14]. For example, a study in Japan found that SKT of participants had a linear correlation with PET value, and it was also affected by individual differences significantly, especially gender and figure [15]. In addition, physiological parameters such as SaO2 [16], HR [17], HRV [18] were also used in thermal comfort evaluation.

Based on the above presentation, there are few outdoor thermal comfort studies combined with physiological parameters especially in coastal cities. Therefore, the purpose of this study was to investigate the changes of thermal comfort and physiological responses of participants in two urban parks (one is located inland and one is located along the coast), moreover, to verify the predictive accuracy of physiological parameters for thermal comfort.

Firstly, we employed weather stations to collect microclimate parameters of the seven points on two experiment days, including Ta, Rh, Ws and Sr. Secondly, questionnaires were conducted to evaluate participants' thermal comfort under different environment,

Fig. 2. Location of two parks.

simultaneously with measurement of the participants' physiological parameters, including SKT, SaO2, HR and HRV.

2. Methods

2.1. Study areas and sample selection

Qingdao, a coastal city in China, is located between 119°30′ to 121°00′ east longitude and 35°35′ to 37°09′ north latitude. It is characterized by the temperate monsoon climate with obvious maritime climate characteristics due to the proximity to the ocean. August is the hottest month with an average temperature of 25.3 °C and January is the coldest month with an average temperature of −0.5 °C. Further, the wind direction is predominantly from the southeast and the annual average relative humidity is about 73%.

Two parks were selected for the study, as shown in Fig. 2. Yan'er Island Mountain Park is located in the coastal area of Shinan District, covering an area of 4.6 hm^2. Jiading Mountain Park is located in Shibei District, about 6.1 km near the sea, covering an area of 18.37 hm^2. We scrutinized the features of the green space and selected seven points with different Sky View Factor (SVF) for field measurements, as shown in Fig. 3.

2.2. Microclimate

Two consecutive days (September 30 & October 1, 2021) with typical weather condition were selected to conduct field measurements. Qingdao had not yet entered the meteorological autumn during the experimental period, which was the latest since 1971 (Qingdao Meteorological Bureau). Seven Kestrel NK-5500 series weather stations and seven TES-1333R series solar power meter were employed to measure microclimate parameters, including Ta, Rh, Ws and Sr. All parameters were measured at 1.5 m height above the ground with a 5-min data logged interval from 7:00am to 18:00pm. Measurement range and accuracy of each parameter of the weather stations are shown in Table 1.

2.3. Questionnaire and physiological measurements

2.3.1. Participants

Fifty-two healthy voluntary college students were recruited for the field experiment (Table 2). All participants had no history of cardiovascular or skin disease and had lived in Qingdao for more than 1 year. The experiment required uniform dress as follows: underwear, short-sleeved shirt, sports shorts, cotton socks and sports shoes, total clothing levels of about 0.4clo. In addition, participants were informed not to stay up late and drink alcohol the day before the experiment to ensure physical and mental health during the test.

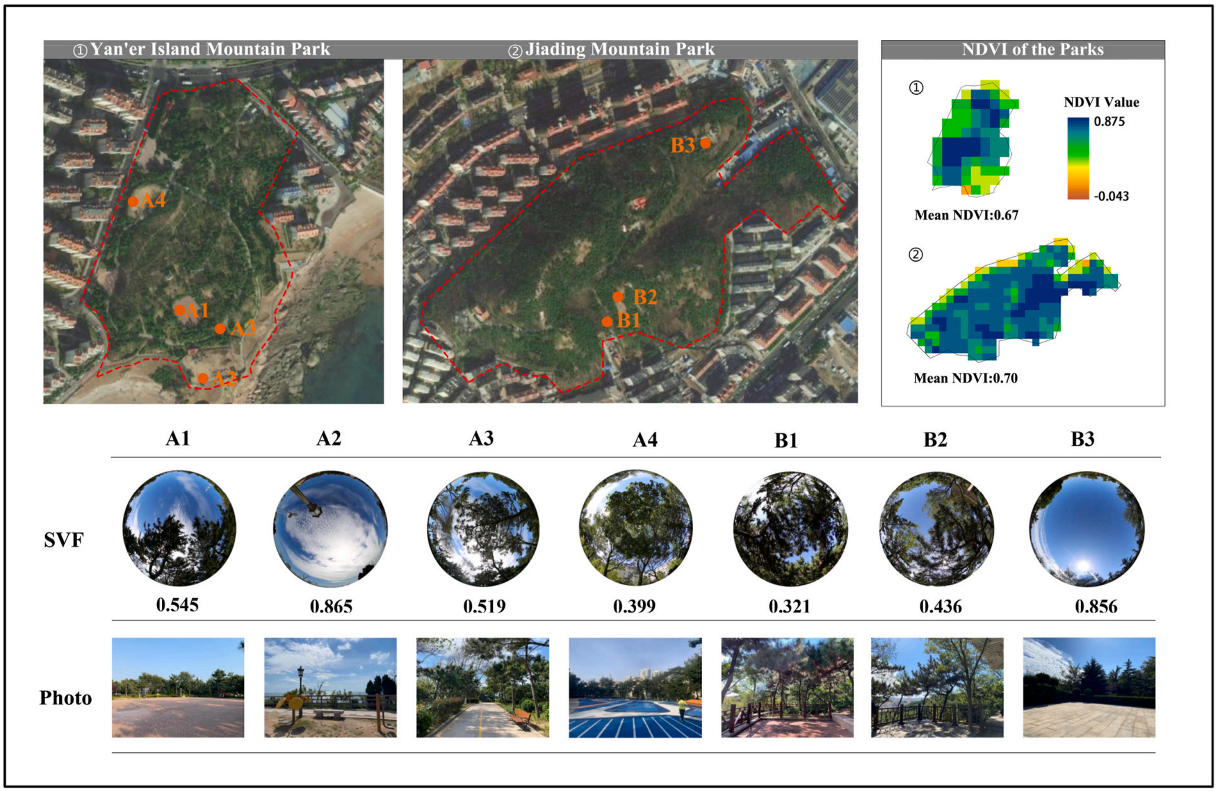


Fig. 3. Information about the seven measurement points.

Table 1
Measurement parameters and specification of equipment.

parameter	Instrument	Valid Range	Accuracy
Air temperature	Kestrel NK-5500 weather stations	−29–70 °C	0.5 °C
Relative humidity		10–90%	±2%
Wind speed		0.6–40 m/s	±3%
Solar radiation	TES-1333R solar power meter	0–2000W/m^2	±10W/m^2

Table 2
Participants' information summary (values are means ± standard deviation).

Gender	Participants(n)	Age(Years)	Height(cm)	Weight(kg)
Male	23	22.5 ± 1.9	176.5 ± 4.1	71.8 ± 10.3
Female	29	22.6 ± 2.7	165.2 ± 5.2	54.4 ± 6.7
Total	52	22.6 ± 2.4	170.2 ± 7.4	62.1 ± 12.1

2.3.2. Experiment design

We divided the recruited participants into two groups with the same number, gender ratio, and physical condition, and measured their physiological parameters in the two parks simultaneously. Before the experiment, the participants rested in the shade for 15 min to stabilize their physiological state. At the same time, we helped the participants to install the experimental instruments on their bodies and explained the experimental procedures again. The experimental sequence for each participant was from point A1 to A4, B1 to B3, and participants were required to sit quietly next to the weather stations at each measurement site for 15 min, including 10 min to acclimatize to the microclimate and 5 min to measure physiological parameters and complete thermal comfort questionnaire (Fig. 4).

2.3.3. Questionnaire design

The questionnaire consists of two parts, the first part is demographic information and the second part is evaluation of subjective thermal comfort, including TSV, TCV, HSV, WSV, RSV. Questions were designed based on five-to-seven-point Likert scales, consistent with ASHRAE [2] (Table 3). Fig. 5 shows some photos of the experimental process.

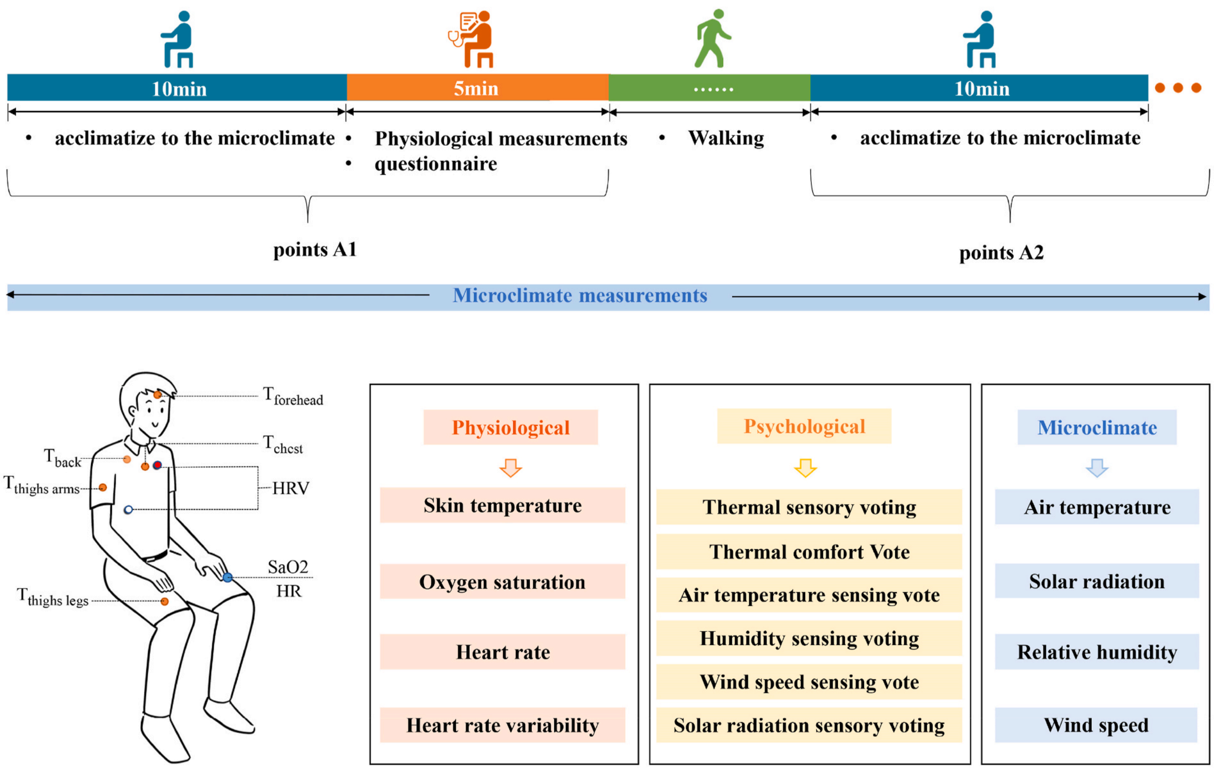


Fig. 4. Experimental procedure.

Table 3
Score level in the questionnaire.

TSV	TCV	HSV	WSV	RSV
☐ −3 Cold	☐ 0 Comfortable	☐ −2 Dry	☐ −2 Weak	☐ −2 Weak
☐ −2 Cool	☐ 1 Slightly uncomfortable	☐ −1 Slightly dry	☐ −1 Slightly weak	☐ −1 Slightly weak
☐ −1 Slightly cool	☐ 2 Uncomfortable	☐ 0 Neutral	☐ 0 Neutral	☐ 0 Neutral
☐ 0 Neutral	☐ 3 Very uncomfortable	☐ 1 Slightly wet	☐ 1 Slightly strong	☐ 1 Slightly heavy
☐ 1 Slightly warm	☐ 4 Unbearable	☐ 2 Wet	☐ 2 Strong	☐ 2 Heavy
☐ 2 Warm				
☐ 3 Hot				

Fig. 5. Field photos of the Experiment process.

2.3.4. *Physiological measurements*

In this paper, physiological parameters such as SKT, HRV, SaO2, HR were collected by physiological monitoring instruments, which are applicable to outdoor environment and sensitive to changes in microclimate environment. Measurement range and accuracy of each parameter of the monitoring instruments are shown in Table 4.

SKT was collected by JK808 multiplex Temperature Tester, and the thermocouple should be glued to the skin and fixed with medical tape during the experiment. Moreover, SKT was collected from five areas for each participant, including forehead, chest, back, thighs arms and thighs legs. The average SKT We calculated based on the percentage of area and the weighting factors for each measurement point were 0.15, 0.19, 0.19, 0.10, 0.37 [19].

HRV describes the variations between consecutive heartbeats, known as R-R intervals [20].HRV analysis is a valid method to evaluate autonomic nervous system function and homeostasis used in medicine [21]. In the analysis of HRV, the power ratio LF/HF in the low frequency band to the high frequency band is a very important indicator, which reflects the relative balance of sympathetic nervous activity and vagus nervous activity. Increased LF/HF indicates increased sympathetic nervous activity and suppressed vagus nervous activity, while sympathetic excitation causes the production of thermoregulatory activity (sweating, skin vasoconstriction) [22]. Some scholars have used LF/HF to study human thermal comfort, and they found that when the human body was in uncomfortable state, LF/HF was significantly higher than that in comfortable state [23]. The HRV was acquired from the ECG data that were recorded using the HeaLink-R211 Heart Rate Recorder (A miniature ECG recorder). After the participants sat quietly for 10 min, we started recording ECG data for 5 min. In the experiment, the 2 lead was used because it can acquire more clear signals and avoid the interference of other leads [24]. The V5 lead was selected and connected to the negative electrode, the Ra (right arm) lead was also selected and connected to the positive electrode (red in color). However, in order to eliminate ECG signal changes caused by arm movements, we moved the measurement point from the right arm to the skin 10 cm below the center of the right clavicle [25].

SaO2 describes the concentration of blood oxygen in the blood, which is an important physiological parameter of the respiratory cycle. SaO2 has now been used by scholars in the evaluation of thermal comfort and has been found to correlate with TSV significantly [16].

HR is the number of beats per minute of the heart and is also used extensively in thermal comfort studies [17]. SaO2 and HR were collected by Contec-CMS50D Oximeter in this experiment.

Table 4
Measurement parameters and specification of equipment.

Parameter	Instrument	Valid range	Accuracy
Skin temperature	JK808 multiplex Temperature Tester	−200–1300 °C	0.2% + 1 °C
Heart rate variability	HeaLink-R211 Heart Rate Recorder	0.04–0.15 Hz (LF) 0.15–0.4 Hz (HF)	±0.01 Hz
Oxygen saturation	Contec-CMS50D Oximeter	70–100%	±2%
Heart rate		30–250bpm	±2bpm

2.4. Statistical analysis

ECG Viewer 1.2 (A software for viewing and converting ECG data recorded by miniature ECG recorders) was used to extract 5 min of ECG data from the participants and then imported into Kubios HRV 3.4.0, a professional software developed by Kuopio University in Finland [26–28]. We eliminated the anomalies by the "Beat correction" function. After that we performed a frequency domain analysis to obtain the ratio of low frequency band to the high frequency band (LF/HF).

Rayman12 [29] was used to calculate PET, which has been widely used in a series of studies about outdoor thermal comfort [30–32]. It has many advantages such as not relying on subjective evaluation results, easy to be understood and not limited by climate type zones.

In order to determine the relationship between the indicators, we used the data analysis software SPSS25.0 and set the significance level at 0.05. Descriptive analysis, correlation analysis, and linear regression were used in the analysis process.

3. Results

3.1. Microclimate

The weather conditions were obtained from the Qingdao weather station, during the 2 experiment days, ranged from cloudy to sunny, with the maximum and minimum temperatures of 28 °C and 20 °C, respectively. Relative humidity was 65%–95%, and southwesterly winds was about 2 m/s.

Table 5 shows the mean microclimate parameters and PET of seven points during the experiment. By compared points with similar SVF in the two parks (A2 vs. B3, A4 vs. B1 and B2), we found that the Rh of the coastal points was significantly higher than the inland points, the Ta of the coastal points was lower than that of the inland points, the Sr at the coastal points was significantly higher than the inland points. In addition, the difference in Ws between inland and coastal was not significant on the experimental day. B2 was located at the top of a hill with an open view, so the wind speed (1.4 m/s) was significantly higher than the other points.

B2,which is inland, had higher Ws(1.4 m/s), lower Ta(26 °C) and lower Sr(117.6W/m^2), making it the point with the lowest PET value(24.8 °C). A2,which is closest to the sea, had the largest SVF and the strongest Sr(436.9 **W/m2**), making it the point with the highest PET value(36.2 °C).

3.2. Thermal comfort

3.2.1. Changes of thermal comfort under different microclimate

A total of 180 data points was collected. Each data point consisted of microclimatic conditions, questionnaire answers and corresponding physiological parameters.

Table 6 shows the mean thermal comfort survey in seven points. Corresponding to the microclimate environment, point A2 had the highest TSV value of 2.33(between "warm" and "hot") and the highest TCV value of 2.75 (between "uncomfortable" and "very uncomfortable"). Point B2 had the lowest TSV value of 0.18 (between "neutral" and "slightly warm") and the lowest TCV value of 1.07 (between "slightly uncomfortable" and "comfortable").

Table 7 shows the correlation analysis for thermal response votes. TSV showed a significant correlation with TCV, WSV, and RSV, with coefficients of-0.62, −0.41, and 0.75, respectively. This reveals that TSV was correlated with TCV significantly, RSV was the most positively correlated with TSV. Furthermore, TCV had a significant correlation to WSV and RSV, with coefficients of 0.35 and −0.67.

We analyzed the correlation between thermal comfort and microclimate, as shown in Table 8. TSV showed a significant correlation with Ta, Rh, Ws and Sr, with coefficients of 0.48, −0.19, −0.18 and 0.72, respectively. This reveals that TSV was most positively correlated with Sr, which is consistent with the results of the previous analysis. And the correlation of TSV with Rh and Ws is weaker. TCV showed a significant correlation with Ta, Rh, Ws and Sr, with coefficients of −0.32, −0.15,0.15 and −0.51, respectively. Similar to TSV, TCV has the most positively correlation with Sr and the weaker correlation with Ws and Rh.

3.2.2. Relationship between PET and Thermal Comfort

We analyzed the correlation between thermal comfort and PET, as shown in Table 8. PET had a significant positive correlation with TSV (0.72**) and had a significant negative correlation with TCV (-0.50**).

Regression analysis was performed to observe the predictive ability of PET on thermal comfort. Firstly, we collated the questionnaires filled out by the participants at each point, and then brought in the environmental parameters corresponding to each questionnaire to calculate the PET values. Linear regression analysis at this stage is shown in Figure 6(a), where we found that thermal

Table 5
Mean microclimate parameters and PET values during experiment days.

point	Yan'er Island Mountain Park				Jiading Mountain Park		
	A1	A2	A3	A4	B1	B2	B3
SVF (%)	0.545	0.865	0.519	0.399	0.321	0.436	0.856
Ta (°C)	26.9	26.6	29.1	25.6	26.1	26.0	27.4
Rh (%)	72.2	73.8	69.2	76.6	67.8	69.2	63.2
Ws(m/s)	0.4	0.3	0.3	0.6	0.5	1.4	0.3
Sr(W/m2)	209.7	436.9	284.9	190.7	84.9	117.6	339.6
PET(°C)	30.6	36.2	35.9	28.1	26.3	24.8	33.6

Table 6
Mean thermal comfort survey in seven points(Values are means ± standard deviation).

	A1	A2	A3	A4	B1	B2	B3
TSV	0.96 ± 1.02	2.33 ± 1.03	1.00 ± 1.29	0.83 ± 1.03	0.21 ± 0.77	0.18 ± 0.93	1.21 ± 1.40
TCV	1.62 ± 0.86	2.75 ± 0.88	1.54 ± 1.19	1.50 ± 0.87	1.21 ± 0.56	1.07 ± 0.65	2.07 ± 0.92
HSV	0.38 ± 0.63	0.83 ± 0.85	0.50 ± 0.76	0.13 ± 0.44	0.32 ± 0.54	0.11 ± 0.49	0.07 ± 0.65
WSV	−0.5 ± 0.65	−0.83 ± 0.75	−0.83 ± 0.75	−0.54 ± 0.64	−0.64 ± 0.77	−0.2 ± 0.67	−1.21 ± 0.62
RSV	0.46 ± 0.71	1.46 ± 0.76	0.13 ± 1.05	0.38 ± 0.99	−0.36 ± 0.81	0.9 ± 0.90	0.29 ± 1.16

Table 7
Correlation analysis for thermal response votes.

	TSV	TCV	HSV	WSV	RSV
TSV	1	−0.62[a]	−0.11	−0.41[a]	0.75[b]
TCV	–	1	−0.16[b]	0.35[a]	−0.67[a]
HSV	–	–	1	−0.17[b]	0.11
WSV	–	–	–	1	−0.26[a]
RSV	–	–	–	–	1

[a] Correlation is significant at the 0.01 level(2-tailed).
[b] Correlation is significant at the 0.05 level (2-tailed).

Table 8
Correlation analysis of thermal comfort and microclimate.

	Ta	Rh	Ws	Sr	PET
TSV	0.48**	-0.19*	-0.18*	0.72**	0.72**
TCV	-0.32**	0.15*	0.15*	-0.51**	-0.50**

**correlation is significant at the 0.01 level(2-tailed)
*correlation is significant at the 0.05 level (2-tailed).

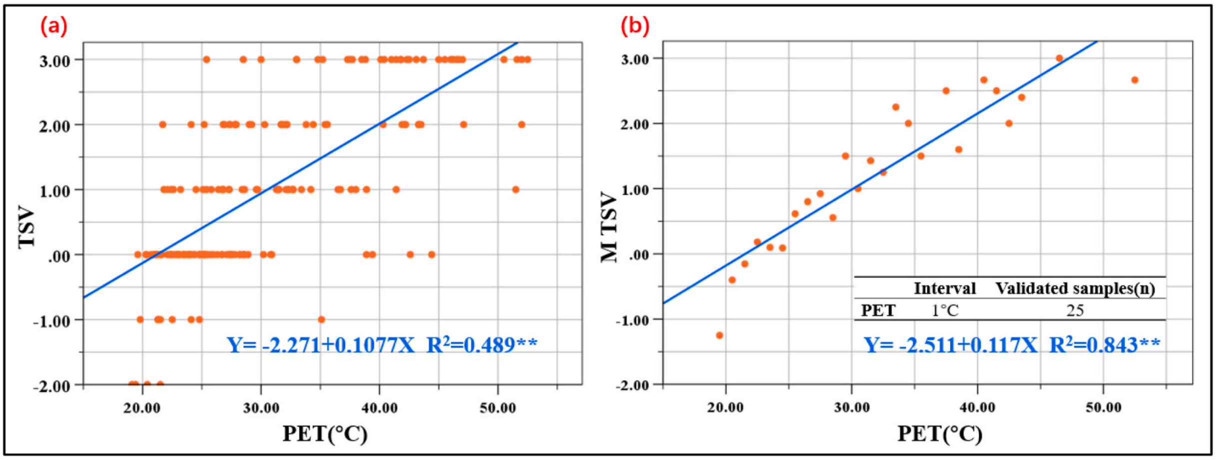


Figure 6. Linear regression of PET and MTSV, **p <0.01(2-tailed).

sensation varied by individual factors in the same thermal environment. Secondly, we calculated the MTSV (Mean Thermal Sensation Vote) per 1°C interval for PET and selected samples with more than 3 votes to reduce the influence of personal factors. We obtained a total of 25 validated samples, and we performed linear regression analysis on these samples (Figure 6 (b)). The above steps are similar to other studies [33,34,35]. The results showed that the R^2 of PET was 0.843 which indicated that PET had a strong ability to predict thermal comfort.

3.3. Physiological Responses

3.3.1. Changes of Physiological Parameters under Different Microclimate

Changes of physiological parameters in seven points were shown in Table 9, in which SKT of the participants were in the range of 30.75°C-36.23°C, LF/HF in the range of 0.22-8.09, SaO2 in the range of 91%-99% and HR in the range of 58bpm-108bpm. In the experiment, we found that individual differences in SKT and SaO2 were relatively small in value, while individual differences in HR

Table 9
Results of physiological parameters in seven points.

		A1	A2	A3	A4	B1	B2	B3
SKT	**MIN**	32.30	31.56	32.19	32.16	32.06	30.75	34.94
	MEAN	33.71	34.37	34.25	34.28	33.70	33.31	33.48
	MAX	34.84	36.23	35.89	36.19	35.45	35.03	31.99
LF/HF	**MIN**	0.22	0.55	0.38	0.38	0.49	0.22	0.86
	MEAN	2.47	3.07	2.22	2.28	2.32	2.03	2.48
	MAX	6.29	8.09	6.54	6.54	6.73	5.35	7.21
SaO2	**MIN**	92.00	93.00	91.00	94.00	95.00	95.00	95.00
	MEAN	96.25	96.54	96.38	96.96	97.46	97.50	97.14
	MAX	99.00	99.00	99.00	98.00	99.00	99.00	99.00
HR	**MIN**	62.00	66.00	60.00	66.00	58.00	58.00	61.00
	MEAN	76.54	81.83	78.58	78.92	76.07	75.07	76.89
	MAX	103.00	104.00	99.00	91.00	108.00	97.00	98.00

and LF/HF were very large. We found that males who exercise regularly had a low HR, while males with a higher BMI were more sensitive to thermal environments and their LF/HF was higher under the same environmental conditions.

Fig 7 (a)–(d) present the changes in the mean physiological parameters of participants of the seven points during experiment. The maximum values of three physiological parameters were found at point A2, including mean SKT was 34.37°C, mean LF/HF was 3.07 and mean HR was 81.83bpm. The minimum values were found at point B2, mean SKT was 33.31°C, mean LF/HF was 2.03 and mean HR was 75.07bpm,respectively.Furthermore, the maximum point of mean SaO2 is B2(97.50%) and the minimum point is A1(96.25%). Fig 6 (e) presents the changes in the mean PET of seven points during experiment. We found that SKT, HR, and LF/HF were similar in rank order of size to PET at each point, while SaO2 was reversed.

Utilizing 180 data points, we analyzed the correlation between physiological parameters and environmental parameters, as shown in Fig. 7 (f). SKT had a significant correlation with Ta and Sr with coefficients of 0.36 and 0.36. SaO2 had a significant correlation with Ta, Ws and Sr with coefficients of −0.26, 0.18 and-0.21 respectively. HR had a significant correlation with Ws and Sr with coefficients of 0.15 and 0.29. However, no significant correlation was found between LF/HF and environmental parameters, which should be due to individual differences.

According to the analysis above, all four physiological parameters were sensitive to microclimate changes of the environment.

3.3.2. Relationship between physiological parameters and thermal comfort

In order to observe the predictive ability of physiological parameters on thermal comfort, we performed Linear regression of physiological parameters and MTSV.

Fig. 8(a) shows the Linear regression of SKT and MTSV. The MTSV for every 1 °C interval was calculated for SKT and 11 validated samples were obtained. The results showed that the R^2 of SKT was 0.803, which indicated that SKT having similar accuracy in predicting participants' thermal sensation with PET (R2 = 0.843, Fig. 6(b)). In addition, we observed that there were points of lower SKT but corresponding to higher TSV, which may be due to skin sweating.

Fig. 8(b) shows the Linear regression of SaO2 and MTSV. The MTSV for every 1% interval was calculated for SaO2 and 9 validated samples were obtained. The results showed that the R^2 of SaO2 was 0.711.

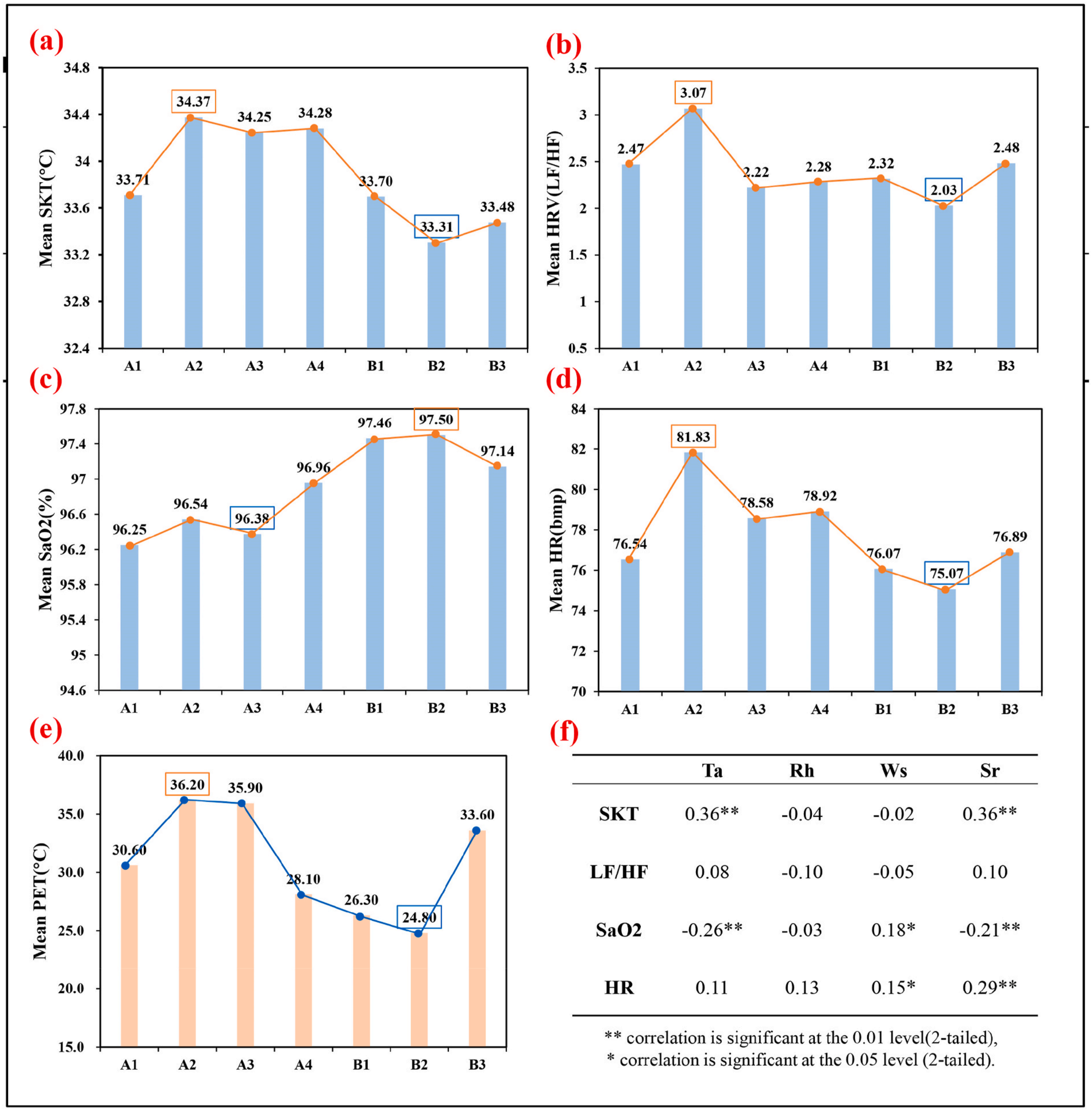
We found a weak linear relationship between MTSV and LF/HF, which maybe because of excessive individual differences in the limited sample size, therefore, we adjusted the research method for LF/HF analysis. Moreover, each participant involved in all points in each park, analysis of the mean LF/HF value for each point can eliminate the effect of individual differences greatly. Based on the above considerations, we performed Linear regression of mean TSV and mean LF/HF for each point, as shown in Fig. 9 (a). The results showed that the R^2 of mean LF/HF was 0.830, which indicated that it has a strong ability to predict changes in thermal comfort among different points.

In the same way as LF/HF analysis, we performed Linear regression of mean TSV and mean HR for each point, as shown in Fig. 9 (b). The results showed that the R^2 of mean HR was 0.767, which indicated that mean HR having similar power in predicting participants' thermal comfort with mean LF/HF.

4. Discussion

By comparing the microclimate parameters of different points, we found that there were significant differences between the microclimates of coastal park and the inland park in the same climatic context. Compared with inland park, measurement points located in coastal park had lower Ta and higher Rh, which should be due to the cooling and humidifying effect of sea. In addition, the Sr in coastal parks was significantly higher than inland parks, which should be due to the stronger radiation, scattering and reflection of sunlight of the seaside atmospheric environment [36].

We found that Sr and Ta had the strongest positive correlations with TSV and TCV by correlation analysis, while Rh and Ws showed a weaker correlation with TSV and TCV. Similarly, WSV was weakly correlated with TSV and TCV, HSV was weakest correlated with TSV and TCV. This reveals that people were more sensitive to changes in Sr and Ta in outdoor environments than Ws and Rh. These results were similar to research of Li [37] and Liu [38], where they found solar radiation and air temperature had the strongest positive correlation with the thermal sensation vote.



	Ta	Rh	Ws	Sr
SKT	0.36**	-0.04	-0.02	0.36**
LF/HF	0.08	-0.10	-0.05	0.10
SaO2	-0.26**	-0.03	0.18*	-0.21**
HR	0.11	0.13	0.15*	0.29**

** correlation is significant at the 0.01 level(2-tailed),
* correlation is significant at the 0.05 level (2-tailed).

Fig. 7. Results and analysis of physiological parameters, a) mean SKT, b) mean LF/HF, c) mean SaO2, d) mean HR, e) mean PET, f) Correlation of physiological parameters with environmental parameters.

Furthermore, we found a high correlation between PET and MTSV through the regression analysis ($R^2 = 0.843$, $p < 0.01$). This is similar to other studies in China, such as a study conducted in Shanghai in which PET were linearly regressed with mean TSV ($R^2 = 0.904$, $p < 0.01$) [34] and a study by Lei in Harbin ($R^2 = 0.766$, $p < 0.01$) [39]. The result shows that the evaluation of thermal comfort by PET is applicable in Qingdao area.

For physiological responses, we found that all four physiological parameters were sensitive to changes of microclimate in the environment and the trend was generally consistent between different points. The strongest correlation was found between SKT and microclimate parameters, it had a significant positive correlation with Ta and Sr. SaO2 was significantly correlated with Ta, Sr, and Ws. HR was significantly correlated with Sr only, while no significant correlation was found for LF/HF. This could be attributed to excessive variation in parameters between participants due to individual differences, including gender, age, and physical condition. The HR of male participants who exercised regularly were significantly lower than that of female participants who usually exercised less during this study. We also found that people with higher body mass index (BMI) were more sensitive to thermal environment and they had higher LF/HF under the same environmental conditions, since the thick fat layer hinders the heat dissipation, therefore the body

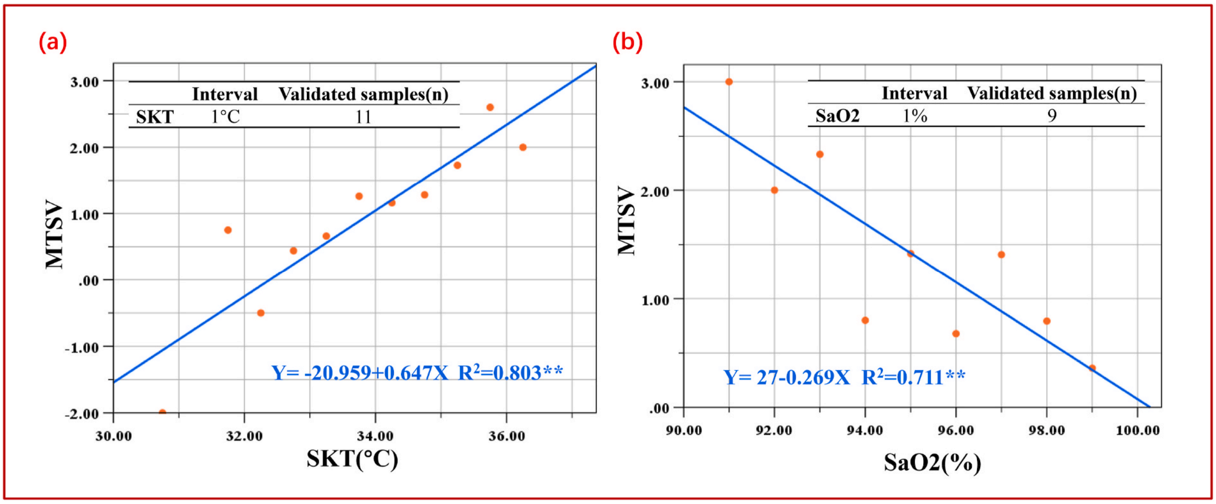


Fig. 8. Regression of physiological parameters and MTSV, a) SKT, b) SaO2, *$p < 0.05$, **$p < 0.01$(2-tailed).

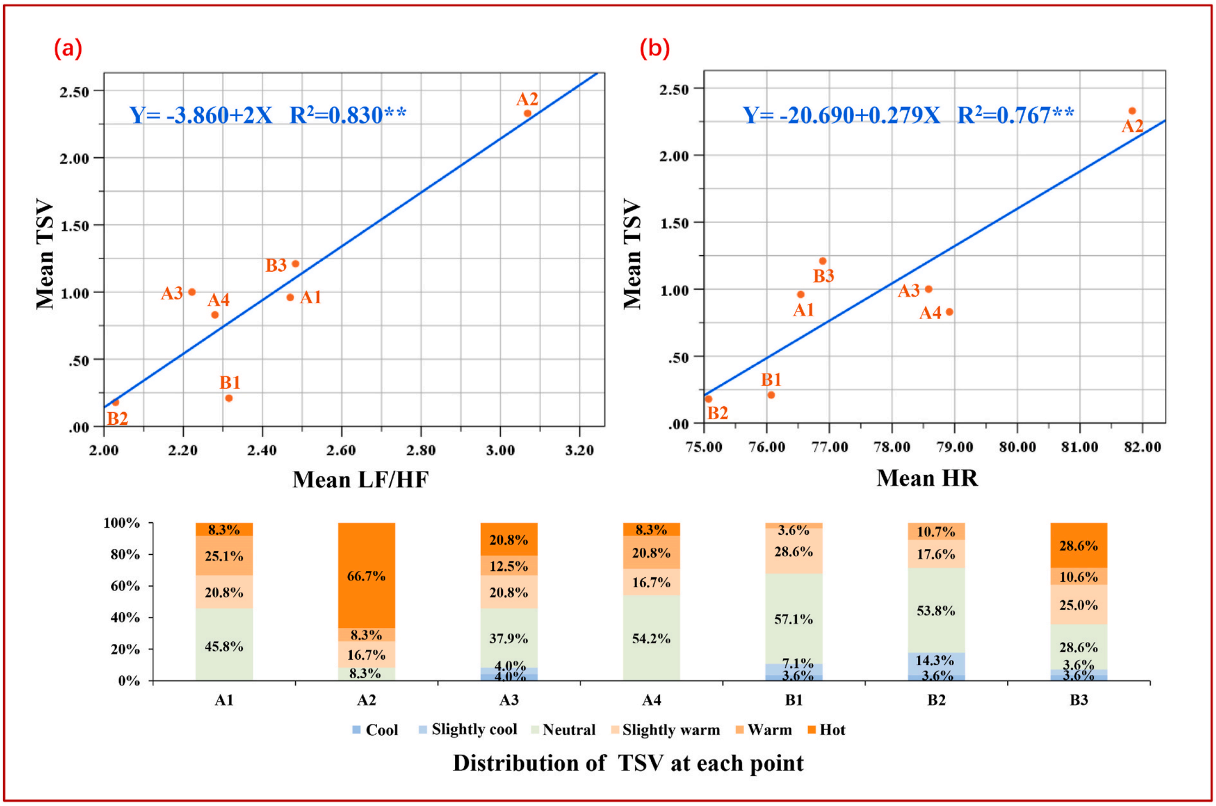


Fig. 9. Regression of mean physiological parameters and mean TSV, a) mean LF/HF, b) mean HR, *$p < 0.05$, **$p < 0.01$(2-tailed).

sweats more easily [24].

In addition, we found that SKT and SaO2 had similar accuracy in predicting participants' thermal sensation with PET by Linear regression. However, HRV(LF/HF) and HR had strong accuracy to evaluate thermal comfort between different points. They are more applicable to longitudinal dynamic surveys for each participant.

Despite these findings, our research had several limitations. First, we did not consider the order of microclimate that participants were exposed to, which is thought to affect their body's thermoregulation through thermal adaptation [40]. We will consider this aspect in our future studies. Secondly, participants in this experiment were young college students, so we did not focus on the effect of individual characteristics of the participants on thermal comfort. Future studies should take physiological characteristics such as BMI, age, and sex into account. Furthermore, considering the decline of park visitors because of new coronavirus, we chose 2 consecutive days (September 30 & October 1, 2021) in order to gather more participants during national holidays, we missed the most typical summer days, although the experiment was still conducted during summer climatical condition in the meteorological sense. We will recruit volunteers in advance to ensure enough participants and conduct experiment at the most typical summer days in future. Finally, because the experiment was conducted outdoors, the instruments were supposed to be battery powered, portable and data storage. Unfortunately, we did not find standard accurate instruments (accuracy of ± 0.1 °C) for SKT measurement that can meet our requirements, so we focused on observing the variation of SKT among different points with eliminating instrument errors as much as possible. In future, we will consider customizing the instruments for measurement of SKT in outdoor environments.

5. Conclusions

In order to investigate the changes of thermal comfort and physiological thermal responses of urban park green space under different microclimate conditions, we organized this experiment. The major findings of this investigation are as follows:

(1) Changes in physiological parameters caused by thermoregulatory activity can reflect the thermal comfort of the human body. SKT, HRV (LF/HF), SaO2 and HR have high correlation with thermal comfort, and can be used as objective evaluation indexes of thermal comfort having high accuracy.
(2) SKT is proved to be an excellent objective indicator of thermal comfort with high reliability, moreover the measurement and calculation process is relatively simple. LF/HF and HR are influenced by individual differences and suitable for longitudinal comparisons of participants' thermal comfort in different microclimate environment.
(3) Evaluation of thermal comfort by PET is applicable in urban inland and coastal parks in Qingdao.

In the hot summer days, coastal parks have lower Ta, higher Rh, and higher Sr compared to inland parks. Moreover, Sr became the most important influence factor of thermal comfort in coastal parks, therefore the designers can create more shaded spaces for people to use in order to improve human thermal comfort.

Authorship contribution statement

Ruirui Zhu: Conceptualization, Supervision, Writing-review and editing, Funding. Xiaotong Zhang: Methodology, Formal analysis, Investigation, Writing-original draft. Lei Yang: Investigation, Data curation. Yibin Liu: Investigation. Yu Cong: Investigation. Weijun Gao: Resources, Supervision, Funding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2022.102044.

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