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Research article

Field measurement study of indoor thermal environment of badminton halls in a hot summer and cold winter region in different seasons in China

Lin Liu [a,b,c], Yong Ma [a,b,c,*], Ruifeng Huang [a,b,c], Mengyao Jia [a,b,c], Gan Liu [a,b,c], Weitao Zheng [a,b,c]

[a] *Engineering Research Center of Sports Health Intelligent Equipment of Hubei Province, Wuhan Sports University, Wuhan, 430079, China*
[b] *Research Center of Sports Equipment Engineering Technology of Hubei Province, Wuhan Sports University, Wuhan, 430079, China*
[c] *Key Laboratory of Sports Engineering of General Administration of Sport of China, Wuhan Sports University, Wuhan, 430079, China*

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ABSTRACT

The indoor thermal environment has a direct impact on human thermal comfort and health. In order to assess the status of the indoor thermal environment of typical sports buildings in hot summer and cold winter climate zones in China, 14 badminton halls in 10 cities in Hubei Province (including 5 venues in Wuhan) in this climate zone are chosen as research objects for field testing of indoor thermal environment parameters in 4 seasons. All the tested stadiums are naturally ventilated in non-event conditions. The results reveal that the average indoor temperature of badminton halls in summer is excessively high (i.e., 31.89 °C), which is higher than the regulation specified in JGJ31-2003 or GB-T18883-2022 on the reference interval of the indoor air temperature of venues in summer, (i.e., (26–28 °C) or (22–28 °C), respectively). The average indoor temperature of badminton halls in winter is too low (i.e., 12.95 °C), and it is lower than the recommendations of JGJ31-2003 or GB-T18883-2022 on the reference interval of the indoor air temperature of venues in winter (i.e., (16–18 °C) or (16–24 °C), respectively), relative humidity and air velocity are in the thermal comfort interval for all seasons, and the indoor thermal environment factors of badminton courts in spring and autumn meet the comfort requirements. The indoor and outdoor temperatures and the relative humidity of badminton courts are highly correlated. The indoor temperature and relative humidity vary according to changes in those factors outdoors, whereas the air velocity is not affected by outdoor changes. In the hot summer and cold winter climate zones, some discrepancies in the indoor temperature variation patterns of badminton halls at various altitudes are detectable. The results of this study aim to provide a solid basis for the development of indoor thermal-comfort standards for sports stadiums in China.

1. Introduction

The indoor thermal environment has a major impact on the physical and mental health, and on the work efficiency, of the occupants of indoor spaces [1–3]. Thermal comfort is a commonly employed factor in the assessment of human responses to variations in

* Corresponding author. Engineering Research Center of Sports Health Intelligent Equipment of Hubei Province, Wuhan Sports University, Wuhan, 430079, China.

E-mail address: mayong@whsu.edu.cn (Y. Ma).

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indoor thermal environmental conditions through the exploration of the relationships between human physiological, psychological, and environmental factors [4]. Thermal comfort is the primary factor influencing the health and overall productivity of occupants of indoor spaces and is more significant in that regard than visual or acoustic conditions, or indoor air quality [5–7]. Air temperature in the thermal environment is the most crucial factor affecting human thermal sensation and thermal comfort [8], and it is the most substantial parameter in the assessment of thermal comfort. The human body is extremely sensitive to variations in air temperature, and indoor air temperature accounts for 46 % of the environmental factors influencing indoor thermal comfort [9]. Air velocity is also a considerably influential factor in the analysis of thermal comfort during indoor activities [10]. In general, air velocity influences the convective heat loss of the human body [11] and alters the heat perception of the human body in a naturally ventilated environment [12]. On the other hand, many investigations demonstrate that the perception of overall thermal comfort is higher at lower indoor airflow rates [9]. Individual metabolic rates rise as the effect of humidity on thermal comfort increases, and the effect of relative humidity on human thermal comfort is not substantial. However, as the metabolic rate rises, the effect of relative humidity on the occupant's thermal comfort is magnified [9]. Relative humidity essentially affects human thermal comfort in environments above 27 °C [13], meaning that relative humidity should only be considered at higher temperatures [14].

In sports facilities, ensuring thermal comfort is of particular significance, as it may affect the performance and health of the athletes. Specifically, in spaces in which physical activities are carried out, the physiological component plays a crucial role, as the athlete's metabolic rate is high and the body therefore produces a consistent amount of heat that must be dispersed into the environment [15]. Physical activity directly impacts the metabolic rate of the human body, and standards of comfort differ at various metabolic rates [16]. The American College of Sports Medicine (ACSM) recommends that the air temperature in sports venues should be kept between 20 °C and 22 °C, and the relative humidity should be less than 60 % [17]. In addition, the health of occupants of buildings is strongly influenced by the indoor thermal environment of the buildings [18]. China is vigorously developing sports in order to improve public health. Furthermore, badminton, a very popular sport, is not restricted by age, gender, or skill, and people of different ages visit badminton courts for professional training, amateur competition, or recreational purposes [19,20]. According to the 2021 China Sports Venue Statistics Survey [21], there are 179,300 indoor sports venues in China, including 32,700 badminton courts, accounting for 18.23 % of those venues. There are special badminton courts in both new and existing venues, as well as gymnasiums that also have badminton courts. The usage rate of badminton courts remains high throughout the year, and it is of particular note that following the COVID-19 pandemic ever more people are participating in indoor badminton. Interestingly, the intensity of the physical activity involved could reduce human sensitivity to the indoor thermal environment [22]; an investigation on the evaluation of indoor thermal-environment quality in sports buildings indicated that exercisers will require less satisfaction with the thermal ambient temperature [23].

The indoor thermal environment also has a crucial impact on human thermal comfort, and in this area of study, a large number of explorations have focused on the indoor thermal environment of residential spaces [24,25], office buildings [26,27], educational buildings [28], and large commercial buildings [29,30]; nevertheless, there exist few relevant explorations focusing on sports buildings. Moreover, the thermal comfort standards in China should be updated according to local climates and to people's living environment [31]. Hubei Province is situated in central China, where the climate typically features hot summers and cold winters. Indoor thermal-environment testing of badminton courts located in places with such environmental conditions has not been conducted by scholars. Therefore, typical badminton stadiums and venues in all prefecture-level cities in Hubei Province were selected in the current investigation as the research object. Research work performed by other investigators indicated that the vast majority of venues in China do not turn on their air-conditioning systems during normal opening hours; the cooling and heating facilities are only used for large-scale events organized by the government. In other words, air-conditioning equipment is not routinely utilized on a daily basis, and natural ventilation is the customary indoor environment in these venues. The main purpose of this study is to establish the indoor thermal environment of badminton courts by performing the four-season test and to present the current situation as well as the demand data for the design of thermal comfort conditions relying mainly on the natural ventilation mode during regular use of the courts. The indoor thermal-environment evaluation standards for office, residential, educational, and commercial buildings, which are commonly applied in domestic and foreign thermal comfort contexts in China, present problems of applicability in evaluating the indoor thermal environment of badminton halls, owing to varying geographical locations, building functions, and crowd activities.

At present, there have been research results on the indoor air quality of badminton stadiums in this climate zone [32], and only the spring and autumn were studied, and there was no research on the current status of the indoor thermal environment, and our study included four seasons, spring, summer, autumn, and winter. At the same time, there is no special evaluation standard for the indoor thermal environment of badminton halls in China, and all badminton halls are evaluated according to the requirements of "Indoor Air Quality Standards" (GB/T18883-2022) and the design code for sports buildings (JGJ31-2003), and ASHRAE 55–2017 standards. Therefore, this study tested the indoor thermal environment parameters of badminton halls in different areas of Hubei Province in hot summer and cold winter climate zones in different seasons, and selected the thermal environment parameters of temperature, relative humidity and wind speed that the human body is most likely to feel and compared them with the existing national standards, so as to assess the current status of the indoor thermal environment of these badminton halls, and at the same time, to study the relationship between the number of people and the length of the sport on the thermal environment parameters, and the results achieved from the current work will provide solid support for the development of indoor thermal comfort standards for sports venues in China.

2. Methodology

2.1. Test subjects

In the vast country of China, there are five building climate zones from north to south (see Fig. 1a), which are as follows: the severe cold region, the cold region, the hot summer and cold winter regions, the hot summer and warm winter regions, and the mild region. Hubei province belongs to the hot summer and cold winter climate region and is located in central China, which spans from 108° to 116° east longitude and 29°–33° north latitude, with an east-west length of about 740 km and a north-south width of about 470 km. Hubei Province is located in a subtropical region, with four distinct seasons: long summers and winters, and short spring and autumn seasons, influenced by the monsoon; the climate is characterized by hot summers and cold winters. Throughout the year, January is the coldest month, with an average temperature of 2–4 °C; July is the hottest month, with an average temperature of 29 °C; the extreme maximum temperature can reach 40 °C.

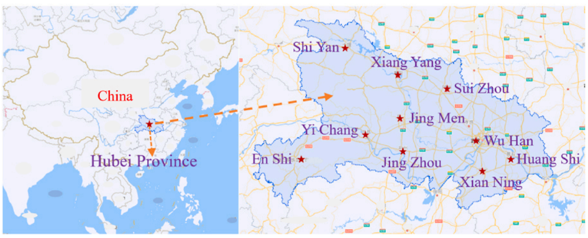
In this study, cities in Hubei Province were considered according to the characteristics of their geographical distribution and their resident populations, and 10 cities were finally selected for the measurement of the current status of thermal environment factors in indoor badminton courts, as presented in Fig. 1b and c and Table 1. The western, eastern, and central areas of Hubei Province exhibit high, low, and flat terrains, respectively, and the elevation of the terrain gradually increasess from east to west. To inspect the influence on the indoor thermal environment of badminton courts at various altitudes in the same climatic region, the test subjects are grouped as follows: the cities with high altitude located in the mountainous region (MR) (altitude greater than 500 m) are Enshi, Yichang, and Shiyan; the cities with middle altitude located in the hilly region (HR) (altitude 100 m–500 m) are Xiangyang, Suizhou, Huangshi, Xianning, and Jingmen; and, finally, the cities located in the plain region (PR) (altitude less than 100 m) at low altitude are Jingzhou and Wuhan.

The planned test is to be conducted in 14 badminton halls in 10 cities in Hubei Province (including 5 venues in Wuhan), as presented in Table 2; the test locations have a long history of usage as badminton venues. There are venues with special badminton training halls, complexes, and gymnasiums(see Fig. 2). During the test, all venues are to be ventilated naturally.

2.2. Test method

According to the "Evaluation Standard For The Indoor Thermal Environment in Civil Buildings", 5 equal points on 2 diagonal lines inside the venue are selected as the test points [33] (see Fig. 3). In selecting test points, we avoid doors, windows and other locations to minimize the impact of outdoor factors on the measurement results. The test duration for each test point is 5 min, when the parameter fluctuation of the test is relatively smooth, start recording data; the testers wear masks and record the values after the instrument has monitored the stability, and the test is performed every 2 h. According to ISO7726 [34], the measurement height is about 1.1–1.5 m from the ground [35], and the average value of the 5 measuring points is taken as the measurement value at each moment.

(a)



(b) (c)

Fig. 1. Distribution of test subjects: (a) China climate zone; (b) topographic map of Hubei Province; (c) the geographical distribution of test cities.

Table 1
City information.

City	Populations	Location	City	Populations	Location
Wuhan	11,212,000	Eastern	Enshi	3,390,000	Southwest
Xiangyang	5,680,000	Northwest	Jingmen	2,897,500	Central
Jingzhou	5,570,100	Central	Huangshi	2,689,300	Southeastern
Yichang	4,137,900	Southwest	Xianning	2,548,400	Southeastern
Shiyan	3,398,000	Northwest	Suizhou	2,221,000	Northern

Table 2
Badminton courts information.

No	City	Badminton Hall	Note
WH1-5	Wuhan	Wuhan Sports University Badminton Hall (WH1), Tongji Medical College Badminton Hall (WH2), Youth Palace Badminton Center (WH3), Wuhan Sports Center Badminton Hall (WH4), Hongshan Gymnasium (WH5)	WH1: space size 2000 m^2; space height >9 m; naturally ventilated WH2: built with traditional reinforced concrete; natural ventilation WH3: built with steel-frame structure and glass; simple maintenance structure; natural ventilation WH4: built with traditional reinforced concrete; air conditioning and ventilation system WH5: space size 14,800 m^2; space height 25 m; air conditioning and ventilation system
XY	Xiangyang	Xiangyang Gymnasium	Space size 20,000 m^2; space height 30 m; air conditioning and ventilation system
JZ	Jingzhou	Yangtze University Badminton Hall	Naturally ventilated
YC	Yichang	China Three Gorges University Badminton Hall	Built with traditional reinforced concrete; natural ventilation
SY	Shiyan	Shiyan Sports Center Badminton Hall	Space size 3109.13 m^2; space height >9 m; naturally ventilated
ES	Enshi	Enshi Nationalities Gymnasium	Space size 7400 m^2, space height >9 m, naturally ventilated
JM	Jingmen	Jingmen Sports Culture Center	Space size 16,938 m^2; space height 32 m; air conditioning and ventilation system
HS	Huangshi	Huangshi Sports Center	Space height 33.71 m; air conditioning and ventilation system
XN	Xianning	Hubei University of Science and Technology Badminton Hall	Built with steel-frame structure and glass; simple maintenance structure; natural ventilation
SZ	Suizhou	New Kangle Badminton Hall	Built with steel-frame structure and glass; simple maintenance structure; natural ventilation

Fig. 2. Site photos of some test subjects.

2.3. Instruments and evaluation

The measured indoor environmental parameters mainly include air temperature (T_a), relative humidity (*RH*), and air velocity (*V*) (see Fig. 4a, (b), (c)). Furthermore, the test instruments consist of temperature and relative humidity measuring instruments and wind velocity meters supplied by Testo Instruments. The specific models and parameters of these apparatuses are provided in Table 3.

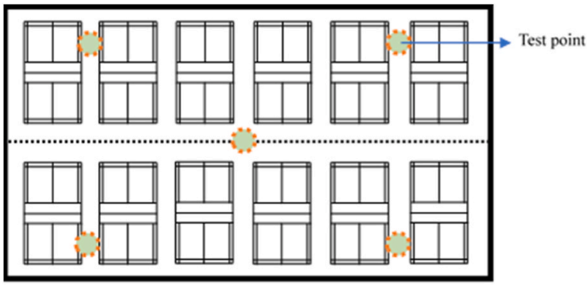


Fig. 3. The test locations of the badminton courts (5 test points in each hall).

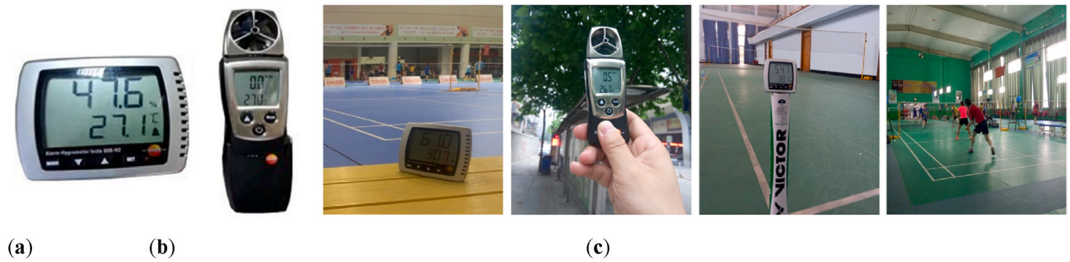


Fig. 4. Test tools and test site: (**a**) temperature and relative humidity measuring instrument; (**b**) anemometer; (**c**) testing site.

Table 3
Profile of the instrument parameters.

Instrument	Model	Parameters	Range Measurement	Accuracy
Temperature and relative humidity measuring instrument	Testo 608-H2	T_a	−10~+70 °C	0.5 °C
		RH	2~98 %	2 %
Anemometer	Testo 410-2	V	0.2–20 m/s	0.1 m/s

2.4. Test time

Before the test, the research team systematically analyzed the climate of each season over many years in 10 cities and selected the representative climate characteristics of each season utilizing the statistics from each of the seasons analyzed. The selected test days were representative of the climate in each season and the duration of the tests was set from 10:00 a.m. to 8:00 p.m. The test team remained in the venue to perform measurements during the closure period at noon, the test was recorded every 2 h; the tests were conducted in four seasons, as shown in Table 4.

3. Results and discussion

3.1. Variation in number of people playing at different times

In the test of indoor thermal environment parameters, statistics were gathered on the number of badminton players in the badminton hall at 6 different times, as shown in Fig. 5. The sum of the daily average number of players in 14 venues was 308 in spring (Figs. 5a), 351 in summer(Figs. 5b), 583 in autumn(Figs. 5c), and 343 in winter (Fig. 5d). Since the Huangshi Sports Center holds badminton competitions in autumn, more people play in the venue at that time; the ventilation and cooling system is not turned on during the tournaments. The statistical distribution pattern of the number of players present at various times shows that the number of people in the venue is generally higher at 4 points: 10:00, 16:00, 18:00, and 20:00 (Fig. 5e); consequently, the increase in the number of people exercising and the accumulated duration of periods of exercise have a considerable impact on the factors influencing the

Table 4
Test schedule.

Season	Testing Time	Season	Testing Time
Spring	14–29 May	Summer	23 July–6 August
Autumn	20–30 October	Winter	10 January–1 February

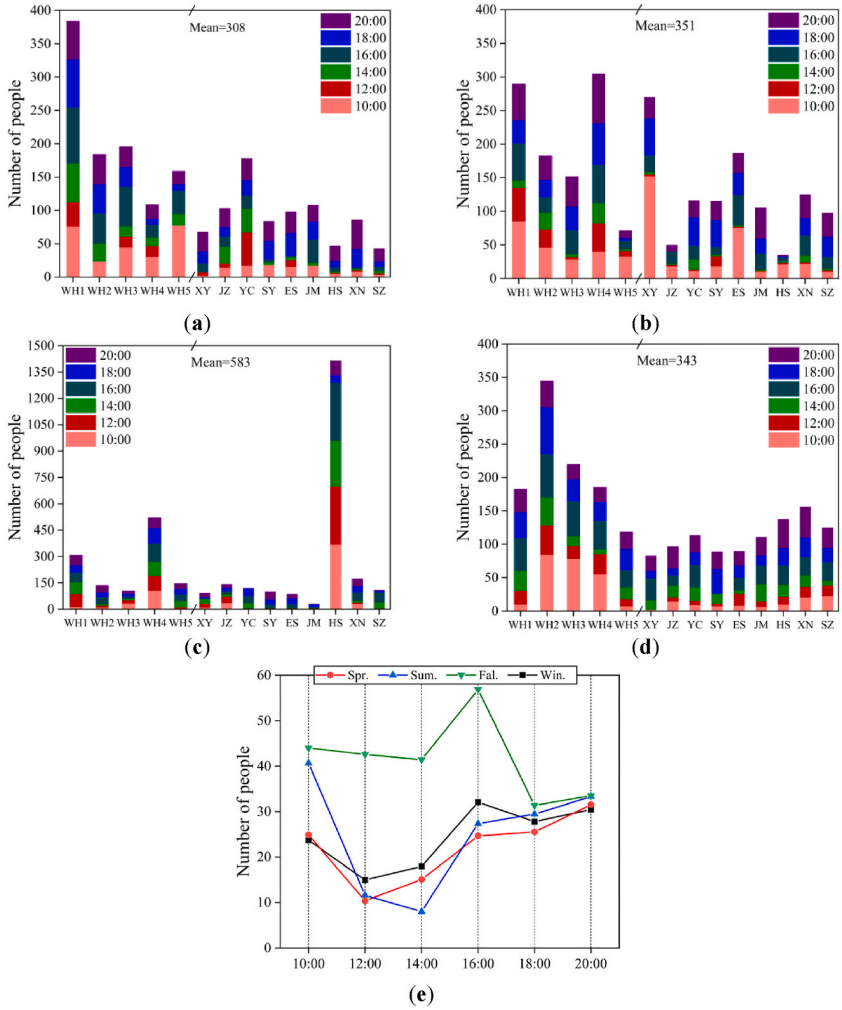


Fig. 5. Statistics on the number of people in 14 test venues in different seasons and at different times: (**a**) the total number of people in spring; (**b**) the total number of people in summer; (**c**) the total number of people in autumn; (**d**) the total number of people in winter; (**e**) the average number of people at different times.

indoor thermal environment of the badminton halls [20].

3.2. Temperature

As can be seen in Table 5, the average indoor temperature in the badminton court of 20.81 °C in autumn is an exception, as it corresponds to the ACSM [36] recommended temperature interval. The temperature of 31.89 °C in summer is much higher than this interval, whereas 12.95 °C in winter is much lower than the interval, with only the spring being moderately closer to it at 23.95 °C.

Table 5
Average indoor and outdoor air temperatures of 14 test venues at various times of the day in four seasons.

Time	Spr/in	Spr/out	Sum/in	Sum/out	Fal/in	Fal/out	Win/in	Win/out
10:00	22.12	22.80	30.83	30.11	20.57	17.69	11.24	10.94
12:00	23.43	25.25	31.66	32.25	20.87	18.83	13.26	13.76
14:00	24.73	26.59	32.03	34.44	21.55	18.78	14.20	15.26
16:00	25.10	26.05	32.53	34.55	20.88	18.37	15.23	13.26
18:00	24.56	24.89	32.40	33.26	20.96	18.17	12.55	10.53
20:00	23.76	23.04	31.88	31.07	20.00	17.11	11.11	8.35

Note: The temperature of 14 venues at each test time is counted, and the average value is considered as the current time's temperature value. Additionally, the expressions "Win", "Spr", "Sum", and "Fal" stand for winter, spring, summer, and fall, respectively, while "in" and "out" specify the indoor and outdoor air temperatures, respectively.

As is shown in Fig. 6b, in Hubei province (i.e., in a hot summer and cold winter climate region), only the indoor thermal environment of badminton courts in spring and autumn throughout the year is in line with, or close to, the comfort level for indoor sports environments recommended by the ACSM, and the deviations from comfort intervals in summer and winter are therefore of note [17]. The main reason for these deviations relates to the ventilation and cooling systems at the venues. The temperature recommended by the ACSM is the comfort temperature interval achieved with cooling and heating systems active; however, none of the venues in this study turned on their cooling and heating systems during the investigation and testing period. Instead, only natural ventilation was provided, principally through the opening of doors and windows.

The plotted statistical results in Fig. 5b reveal that the summer heat did not discourage badminton players, and the sum of the average daily number of participants in the summer reached 351, surpassing the winter and spring participation rates, but it was less than the average daily number of participants in the autumn, a fact that is consistent with the findings of Liu (2017) [37], and Xu et al. (2022) [38]. It implies that people who live for a long time in hot summer and cold winter regions have higher heat tolerance in high-temperature environments [37] with a thermoneutral temperature of up to 26.28 °C, which far higher than the comfort temperature range recommended by the ACSM for exercise sites [37].

In the “Hot Environment-Estimation Of The Heat Stress On Working Man Based On The Wet Bulb Globe Temperature-Index” standard [39], the maximum acceptable temperature for an active population in a hot environment (i.e., the maximum thermal environment working temperature) is 33 °C for people with specific high-temperature adaptation. This standard chiefly assesses the heat-load criteria for people performing physical work for periods of more than 1 h. Since badminton is mostly specified as a physical activity lasting longer than 1 h, we can employ this standard for the evaluation of the thermal environment. The results depicted in Fig. 6a indicate that the indoor temperature of the badminton court in summer is mainly in the range of 30–36 °C, exceeding a temperature of 33 °C for 40.08 % of the time. The data set out in Table 6 demonstrate that the average temperature in summer is 31.89 °C, with a maximum temperature of 38.8 °C. The test results reveal that, with only natural ventilation in indoor badminton courts in Hubei Province (i.e., in the hot summer and cold winter climate region), the indoor temperature in summer exceeds the upper limit of the recommended operating temperatures in the national regulations.

According to the State Administration for Market Regulation and Standardization Administration of China and the “Indoor Air Quality Standards“ (GB/T18883-2022) [40], as presented in Table 7, which implemented on February 1, 2023, the comfort range for indoor temperature is 22–28 °C in summer and 16–24 °C in winter. As shown in Table 5, the average temperatures during the test period in spring and autumn meet the requirements of the comfort range indicated by the standard, while only very few periods in summer and winter are in the comfort range; for the majority of the time, the indoor temperature does not meet the standard requirements. The results in Fig. 5b–d showing the number of people indicate that, although the indoor thermal environment of badminton courts in winter and summer does not meet the comfort requirements of the GB/T18883-2022 standard, the number of exercisers is greater then than it is in the spring, It may be argued that badminton players love the sport and still want to practice it even in unfavorable temperature conditions. Fig. 6b also shows that the indoor temperature of badminton courts in summer is within the acceptable range stipulated by GB/T 17244-1998, and at the same time, we find that the number of people who play sports in summer is also higher from the statistics of the number of people who play sports, which reveals that the applicability of the GB/T18883-2022 standard in evaluating the indoor thermal comfort of badminton courts requires supplementary discussion. With a 90 % voter satisfaction interval of 19.6–27.9 °C, the ASHRAE 55–2017 [41] comfort interval is lower than that of GB/T18883-2022, and it cannot assess more precisely the indoor thermal comfort of badminton courts in hot summer and cold winter climate zones. As a result, GB/T18883-2022 is more suitable than ASHRAE 55–2017 in assessing the indoor thermal environment of China’s badminton courts.

To further examine the influence of altitude on the thermal environment in hot summer and cold winter climate regions, a comparison between the results obtained from regions with different altitudes was carried out. Fig. 7 illustrates the statistical graphs of the indoor temperature of badminton courts in various altitude regions in 4 seasons. As shown in Fig. 7a, spring represents the mildest season of the year, and the temperatures inside badminton halls are moderately close in the three different elevation regions, where the temperature of PR is the lowest, that of HR varies smoothly, and MR exhibits the largest temperature variation. The results depicted reveal that the highest temperature is associated with MR and reaches 26.36 °C at 14:00, but the temperatures in all three regions

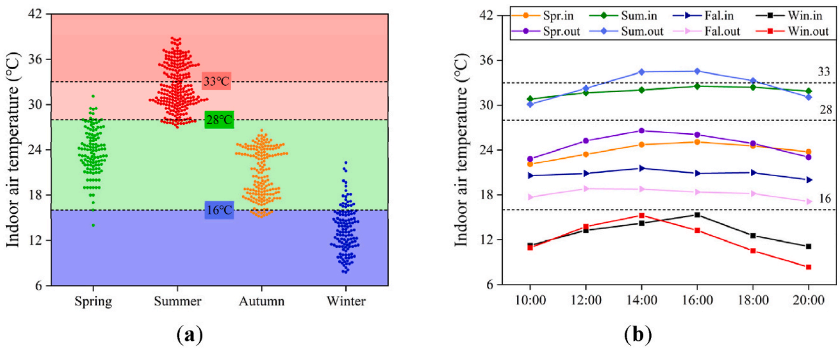


Fig. 6. Indoor (outdoor) temperature range distribution of badminton courts in various seasons in 14 venues: (**a**) temperature distribution; (**b**) temperature trend.

Table 6
Statistical summary of the indoor environmental parameters and comfort-related indices.

Parameters	Spring			Summer			Autumn			Winter		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
T_a (°C)	23.95	31.1	14	31.89	38.8	27	20.81	26.6	15.1	12.95	22.3	7.8
RH (%)	62.95	80	44.3	64.43	86.8	45.4	72.33	87.9	50.6	47.5	68.7	20.4
V (m/s)	0	0	0	0.02	0.2	0	0	0	0	–	–	–

Note: The average values of the measured parameters in different seasons are evaluated for 14 venues, and the mean, maximum, and minimum values of each parameter in all the tested venues in that season are presented.

Table 7
Evaluation standards.

Standard	T_a	*RH*	*V*
GB/T 18883-2022	Sum.22–28 °C Win.16–24 °C	Sum.40–80 % Win.30–60 %	≤0.3 m/s
ASHRAE55-2017	19.6–27.9 °C	–	–
JGJ31-2003	Sum.26–28 °C Win.16–18 °C	Sum.55–65 % Win. >30 %	≤0.2[a] m/s ≤0.5 m/s
GB/T 17244-1998	≯33 °C	–	–

[a] . Note: air velocity necessities in badminton, table tennis, and other activities.

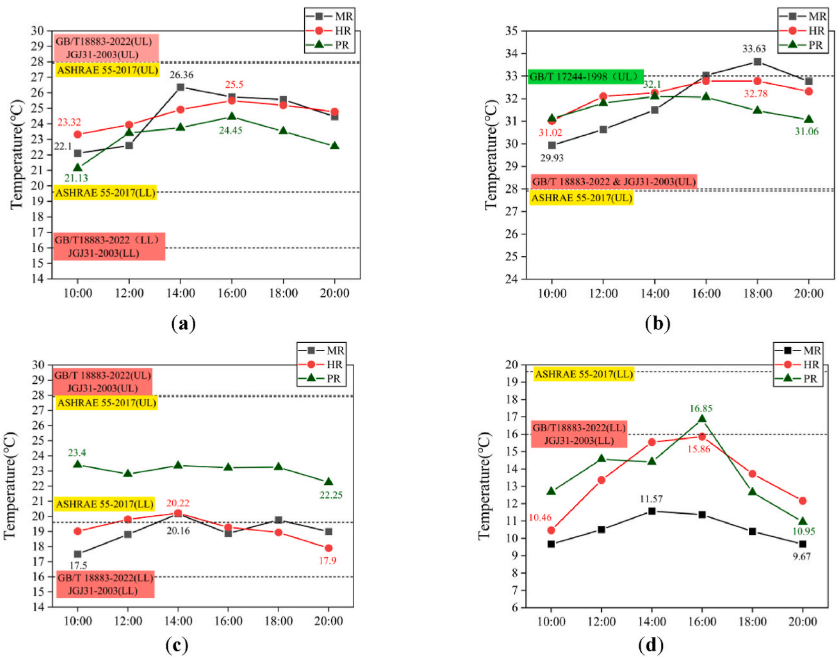


Fig. 7. Indoor temperature of badminton courts at different altitudes and in different seasons: (**a**) spring; (**b**) summer; (**c**) autumn; (**d**) winter. (UL) indicates the upper limit of the standard; (LL) indicates the lower limit value of the standard.

generally meet the thermal comfort interval requirements specified in ASHRAE 55–2017, GB/T18883-2022, and the design code for sports building (JGJ31-2003) standards [42].

As presented in Fig. 7b, summer represents the hottest season of the year, with extremely high temperatures reaching 44.6 °C in 2022, and the highest measured indoor temperature during this test was measured as 38.8 °C (see Table 6). Among the 3 regions with various altitudes, MR exceeds the upper limit (UL) of 33 °C at 16:00 for the operating temperature in the thermal environment specified by GB/T17244-1998 [39], and the indoor temperature of the badminton hall in both HR and PR exceeds the upper limit (UL) of the thermal environment comfort interval in summer specified by the ASHRAE 55–2017, GB/T18883-2022, and JGJ31-2003 standards. As demonstrated in Fig. 7c, among the 3 regions with different elevations in autumn, the PR temperature is the highest, and the temperature during the test period is commonly in agreement with the ASHRAE 55–2017, GB/T18883-2022, and JGJ31-2003 standards. Further, the HR and PR temperatures exceed the lower limit of temperature (LL) in the comfortable interval specified in

ASHRAE 55–2017 for most of the time, but are in line with China's GB/T18883-2022, JGJ31-2003 (sports building design code) comfort interval temperature requirements. As shown in Fig. 7d, winter is the coldest season of the year, and the highest temperature is detected in MR while the highest temperature is 11.57 °C, which is far below the LL level of winter temperature required by the ASHRAE 55–2017, GB/T18883-2022, and JGJ31-2003 standards. Additionally, the temperatures of HR and PR areas at noon are close to the lower limit values (LL) of the GB/T18883-2022 and JGJ31-2003 standards, but much lower than the LL requirement of the ASHRAE 55–2017 standards.

Temperature is the most crucial factor in investigating the influence of thermal comfort in indoor thermal environments [38]. By classifying 14 badminton courts by altitude and comparing the indoor temperatures of MR, HR, and PR, it is found that MR exhibits the lowest temperatures in winter and autumn and the highest temperatures in spring and summer owing to the impact of altitude. The temperature of HR is in the middle range of those of the three zones, although the temperature varies noticeably in winter; the other seasons' temperature variations are relatively mild, being of the minimum amplitude of the three regions. As regards PR, the highest temperature is observed in winter and autumn, while the lowest is detectable in spring, and in summer in the afternoon and evening. The variations in altitude and natural environment have a relatively remarkable impact on the indoor temperature of badminton courts in hot summer and cold winter climate regions in the same season. This implies that, in evaluating the thermal comfort of the indoor thermal environment of the sports environment in hot summer and cold winter climate regions, the altitude of the climate regions should also be considered. At the same time, when designing a badminton court in the same climate zone, the influence of the altitude factor needs to be taken into account.

3.3. Relative humidity (RH)

Relative humidity is an important environmental factor that could influence the thermal comfort conditions of any building [43]. In warm environments, discomfort may be caused by too much moisture on the skin owing to high levels of humidity. Experimental investigations have revealed that skin humidity is a major reason for discomfort in conditions of high humidity [43].

Relative humidity is regarded as one of the evaluation indicators for thermal comfort in the indoor thermal environment. The indoor air quality standard GB/T18883-2022 recommends that the relative humidity in the comfort interval is 40–80 % in summer and 30–60 % in winter. The sports building design code JGJ31-2003 proposes that the relative humidity in the indoor comfort interval of sports stadiums should meet the design requirements of 55–65 % in summer and >30 % in winter. "The design code for heating ventilation and air conditioning of civil buildings" GB50736-2012 recommends that the relative humidity in the comfort interval under cooling conditions is 40–60 % in summer and ≥30 % in winter.

As shown in Table 6, the relative humidity of indoor badminton courts in winter is 47.50 %, which is the lowest for any of the 4 seasons. The relative humidity of indoor badminton courts in autumn reaches 72.33 %, which represents the highest value in any of the 4 seasons. The relative humidity of indoor badminton courts in spring and summer is reported to be 62.95 % and 64.43 %, respectively. According to the relative humidity requirements of the comfort interval of the GB/T18883-2022 standard, the average values of relative humidity in various seasons of the 14 venues studied meet the requirements of the standard. The JGJ 31–2003 standard for the relative humidity comfort interval in summer is relatively low. In fact, this standard is mainly based on the exploitation of heating, ventilation, and air conditioning design conditions relating to the control of indoor thermal environment and relative humidity parameters. Therefore, it is not suitable for evaluating the relative humidity comfort level in naturally ventilated indoor badminton venues. GB50736-2012 is the same as JGJ31-2003, which is also based on heating, ventilation and air-conditioning design under the relative humidity requirements. However, the GB50736-2012 evaluation object is not only designed for gymnasium-type buildings, but also for other civil buildings, and its stipulated relative humidity range is greater than that of JGJ31-2003. Therefore, compared with other current relevant domestic standards for evaluating the relative humidity of indoor thermal environments, GB/T18883-2022 is firmly suggested as a more suitable standard for evaluating the relative humidity of indoor badminton courts where natural ventilation is employed.

As seen in Fig. 8a, according to the GB/T18883-2022 standard, the relative humidity values of the 14 venues tested basically meet the thermal comfort standard in all periods of spring. Nevertheless, there are a few periods where the upper limit of 80 % is exceeded in summer and autumn, and very few periods where the relative humidity falls below the lower limit of 30 % in winter. In the current investigation, the average tested values of relative humidity are calculated for all venues according to time periods, and then the trends of relative humidity variations over time are presented, as demonstrated in Fig. 8b. In a state of natural ventilation, the indoor relative humidity of the badminton hall changes along with the outdoor humidity; the indoor and outdoor relative humidity values remain very close. Only in autumn is the outdoor relative humidity substantially higher than the indoor relative humidity, with outdoor relative humidity exceeding the maximum relative humidity value specified in the GB/T18883-2022 standard. The relative humidity values measured outdoors reveal that the relative humidity values in various areas of Hubei Province in different seasons are generally in line with the requirements of thermal environmental comfort. Furthermore, the venues are essentially examined in conditions of natural ventilation; the indoor and outdoor relative humidity values, and their laws of change, are relatively close; and there is no discrepancy between the sense of relative humidity among the sports participants in the badminton hall and those outdoors.

3.4. Air velocity

Considering that the doors and windows of the venues are closed in winter, and taking into account the measurement data of the other three seasons, the air velocity of the indoor venues in winter should be almost equal to zero, and so the air velocity is not measured in winter. As shown in Table 6 and Fig. 9a, the air velocity is 0 m/s in spring and autumn, and all the test venues are

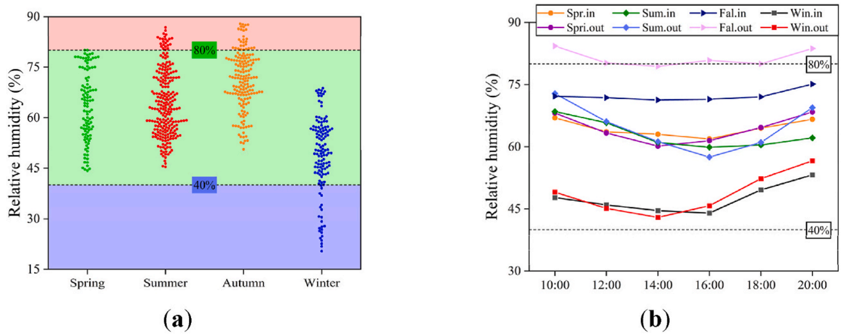


Fig. 8. Indoor (outdoor) relative humidity range distribution of badminton courts in various seasons in 14 venues: (**a**) relative humidity distribution; (**b**) relative humidity trend.

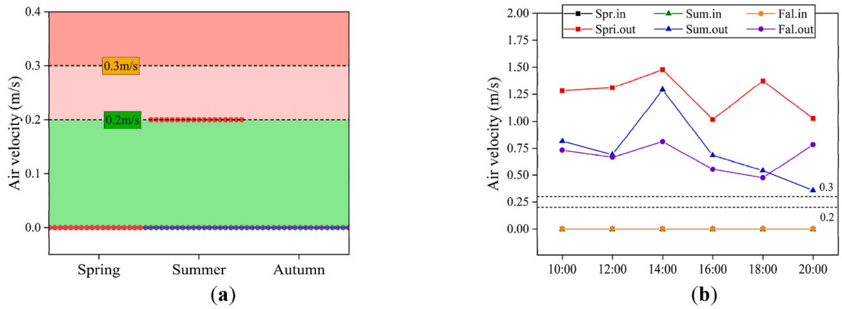


Fig. 9. Indoor (outdoor) air velocity range distribution of badminton courts for various seasons in 14 understudied venues: (**a**) air velocity distribution; (**b**) air velocity trend.

essentially in a windless state, or the air velocity is below the detectable range of the test instrument, the Testo 410-2. The average air velocity in summer is 0.02 m/s, and the maximum air velocity measured is 0.2 m/s. The test result shows that the air velocity is close to 0, which means that the wind speed is very low. This low air velocity may cause a certain stagnation of the air; pollutants accumulate easily, and people feel warmer. When the air velocity is less than 0.2 m/s, there exists a small temperature difference between the horizontal position of the head and the feet among indoor sedentary office personnel [44]. However, in sports environments such as badminton halls, the effects of low or zero air velocity on the indoor thermal comfort of the sports population, or on the badminton players' expectations of the air velocity, are not the same, and there are certain differences from office environments that could become the focus of future research. The results plotted in Fig. 9b indicate that the outdoor air velocity in spring achieves its highest value in the 3 seasons with an average air velocity of 1.24 m/s. The average air velocity in summer is 0.73 m/s with large fluctuations, and the average air velocity in autumn shows its lowest value, 0.67 m/s. In line with the requirement for air velocity of less than 0.2 m/s for the Olympic badminton tournament, all the venues tested appropriately meet the requirements of the badminton tournament in terms of air velocity. In terms of thermal comfort, they also fully meet the comfort requirements of the GB/T18883-2022 standard, which stipulates that the air velocity should be lower than 0.3 m/s in summer and less than 0.2 m/s in winter. This also holds true for the JGJ31-2003 standard that recommends that the air velocity should be less than 0.2 m/s.

4. Limitations and future challenges

The following deficiencies exist in this study of the indoor thermal environment of 14 badminton courts in 10 cities of Hubei Province in the hot summer and cold winter climate region based on field testing methods:

(1) Only temperature, relative humidity, and air velocity of the thermal-environment parameters are monitored; for example, the average radiation temperature has been not observed. This being the case, the comprehensiveness of the indoor thermal environment features and the applicability of the conclusions are somewhat limited.
(2) This investigation conducted the measurement of indoor environmental factors in badminton courts, and further examined the interrelationship between objective parameters and the subjective feelings of personnel in sports, so as to reveal the parameter intervals of different perceptions of people involved in sports and the major factors affecting human thermal comfort in sports environments. In the next study, indices or models, such as PMV, aPMV, SET, adaptive models, and so on, will evaluate thermal comfort and analyze the thermal environment.

5. Conclusions

(1) In the natural ventilation state, indoor temperature and relative humidity vary with outdoor changes, while air velocity is not affected by outdoor influential factors. The relative humidity and air velocity are placed in the thermal comfort interval for all four seasons, and the indoor thermal environment factors of badminton courts in spring and autumn meet the comfort requirements.
(2) The average indoor temperature of the badminton courts in summer is too high (i.e., about 31.89 °C), which is higher than that recommended by JGJ31-2003 or GB-T18883-2022 on the reference interval of the indoor air temperature of venues in summer, (26–28 °C) or (22–28 °C), respectively. The average indoor temperature of the badminton courts in winter is too low (i.e., about 12.95 °C), which is lower than that recommended by JGJ31-2003 or GB- T18883-2022 on the venue indoor air temperature reference interval in winter, (16–18 °C) or (16–24 °C), respectively.
(3) People living in hot summer and cold winter environments for a long time have robust heat resistance to high-temperature environments, and they have a higher thermal neutral temperature. This is much higher than the comfort temperature interval of sports venues recommended by the ACSM and the comfort requirements of the GB/T18883-2022 standard, and the applicability of the GB/T18883-2022 standard in evaluating the indoor thermal comfort of badminton courts should be revisited and further explored.
(4) In the hot summer and cold winter climate regions, there are specific differences in the indoor temperature variation patterns of badminton courts at different altitudes. In evaluating the thermal comfort of the indoor thermal environments of sports venues in hot summer and cold winter climate regions, the altitude of the venues within the climate region should be appropriately considered in the interpretation of results. Standards should be adjusted as required according to different regions of the world, taking into account not only different climatic conditions but also issues of adaptation and acclimatization, as well as cultural considerations.

Ethical review

This study was an on-site test of indoor thermal environment in badminton halls and did not involve any human experimentation.

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Data included in article.

Additional information

No additional information is available for this paper.

Participants consent statement

Participants consented to have these images published.

CRediT authorship contribution statement

Lin Liu: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Yong Ma:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Ruifeng Huang:** Investigation, Formal analysis, Data curation. **Mengyao Jia:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Gan Liu:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Weitao Zheng:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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