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Playing on natural or artificial turf sports field? Assessing heat stress of children, young athletes, and adults in Hong Kong

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ABSTRACT

Exercising in an unusually hot environment may aggravate exertional heat illness. Turf material significantly affects the microenvironment and heat-stress sensation of sports-field users. However, the difference in human-biometeorological effects between different sports-field turf materials demands further investigation. This study compared artificial (AT) with natural turf (NT) fields, investigating three age groups (children, young athletes, and adults), two physical activities (playing soccer and walking), and three heat stress indicators (HI, Heat Index; WBGT, Wet Bulb Globe Thermometer; and COMFA, COMfort FormulA). The results showed heat-stress underestimation by HI and WBGT. In contrast, COMFA, incorporating comprehensive environmental and human physiological parameters, provided a more targeted and reliable heat-stress assessment. COMFA indicated a longer heat-stress duration exercising at AT than NT. Compared to NT, children suffered a 24% longer "Extreme danger" duration at AT in sunny daytime. The AT-NT difference in human-biometeorological effect was limited concerning human convection, evaporation, metabolic heat, and emitted longwave radiation, but was considerable in human absorbed radiation. AT had lower albedo than NT, hence field users absorbed more upward longwave radiation but less upward shortwave radiation, highlighting important control by the radiant environment. NT sports fields are recommended for a healthy outdoor thermal environment, especially for children.

1. Introduction

Cities occupy sizeable land areas where the population lives in an organized way, consuming and developing commercial and cultural activities (Santamouris, 2015). Currently, about half of the world population resides in urban areas (4.2 billion people, 55% of the world population in 2018), and this proportion might increase to 68% by 2050 (Kumar & Sharma, 2020; Nations, 2018). According to the 2020 World Population Data Sheet, 26 countries and territories have more than 40% of their populations living in cities of 1 million or more (Bureau, 2020). The rapidly increasing urbanization has transformed the local and regional land cover and brought various environmental issues such as natural habitat destruction and urban warming (Ren, 2015; Zheng et al., 2021). Urban warming is attributed to both the urban heat island (UHI) and global climate change (Santamouris, 2015). The former, one of the most documented phenomena of climate change (Davtalab & Heidari, 2021; Santamouris, 2015; Tan et al., 2021; Wang, Meng, Tan, Zhang, & Zhang, 2018), is defined as the urban climate with a relatively higher temperature than the surrounding countryside (Oke, 1982). The latter results from greenhouse gas emissions due to human activities. Urban warming brings higher urban temperature and more frequent extreme hot events, intensifying heat waves and harming human health (He, Wang, Liu, & Ulpiani, 2021).

Human health is greatly threatened by heatwaves and extremely hot weather, which may cause heat-related illness (Gu, Huang, Bai, Chu, & Liu, 2016). Such illnesses, including heat edema, heat rash, heat syncope, heat cramps, heat exhaustion, and heat stroke (Howe & Boden, 2007), often occur in people who conduct outdoor activities such as construction, logistics, and sports. Particularly for people in outdoor sports, exertional heat illness (EHI), induced by strenuous exercise in an unusually hot environment, can often overload the thermoregulatory system (Guyer, 2020; Kerr, Marshall, Comstock, & Casa, 2014). One of the highest incidences of EHI is in soccer (Gamage, Fortington, & Finch, 2020) due to its high activity intensity, unshaded sports fields, and season arrangements (with practice seasons beginning in summer), thus exposing players to a high risk of heat morbidity and mortality. Elias (2001) collected a decade of injury reports from 89,500 soccer players aged 9 to 19 and reported a high aggregate rate of heat illness of 2.8 cases/1000 player-hours during hot years. Cheng, Spengler, and Brown

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List of symbols and abbreviations

WBGT	wet bulb globe temperature (°C)
HI	heat index (°C)
COMFA	COMfort FormulA (W/m^2)
AT	artificial turf
NT	natural turf
Ta	air temperature (°C)
RH	relative humidity (%)
WS	wind speed (m/s)
GST	ground surface temperature (°C)
SR	shortwave radiation (W/m^2)
$SR_{downward}$	shortwave radiation downward (W/m^2)
SR_{upward}	shortwave radiation upward (W/m^2)
$LR_{downwad}$	longwave radiation downward (W/m^2)
LR_{upward}	longwave radiation upward (W/m^2)
M	metabolic energy used to heat up the person (W/m^2)
R_{abs}	absorbed shortwave and longwave radiation (W/m^2)
CONV	sensible heat lost or gained through convection (W/m^2)
EVAP	evaporative heat loss (W/m^2)
$LR_{emitted}$	emitted longwave radiation (W/m^2)
K_{abs}	absorbed shortwave radiation (W/m^2)
L_{abs}	absorbed longwave radiation (W/m^2)
RMR	resting metabolic rate (kcal/d)

(2020) estimated the heat stress level of a 10-year-old boy playing football and a 40-year-old man coaching football, and reported that a young athlete's heat stress level would be higher than an adult coach because of their huge difference in metabolic heat production.

Children have been identified as a heat vulnerable group that suffered more from heat injury (Gilchrist, Haileyesus, Murphy, Collins, & McIlvain, 2010) due to their physiological and psychological characteristics. Physiologically, compared to adults, children have a higher surface area-to-mass ratio (Cheng, 2020), higher metabolic rate (Fabbri, 2013), higher skin temperature during exercise (Cheng, 2020), quicker rise in core temperature (Vanos, Herdt, & Lochbaum, 2017), and lower sweat production (Gomes, Carneiro-Júnior, & Marins, 2013). Psychologically, children have less experience coping with or realizing the signs of heat stress than adults (Cheng, 2020). Most children-targeted thermal comfort experimental studies focus on the indoor environment, especially children's thermal sensation in kindergarten or primary school classrooms (Aparicio-Ruiz, Barbadilla-Martín, Martín, & Sanz, 2021; Haddad, Osmond, & King, 2017; Teli, Jentsch, & James, 2012). However, due to direct exposure to sunlight and heat, children's thermal sensation and thermal safety in outdoor activity spaces deserve more attention. Huang, Hong, Tian, Yuan, and Su (2021) conducted field measurements and thermal comfort questionnaire studies in a children's park, and reported that some materials' high surface temperature in the sun might threaten children's thermal safety. Vanos et al. (2017) used heartrate monitors and thermal perception surveys to test children's thermal performance, and reported that children may have a different perception of "thermal (dis)comfort" than adults due to their general lack of experience and knowledge to deal with environmental heat, thus increasing their vulnerability to heat.

To quantify the heat stress experienced by people in sports, various heat stress indicators have been developed, embracing several microclimatic or human physiological variables (Bar-Or, 1983). Previous studies have assessed heat stress in sports using WBGT (Wet Bulb Globe Temperature), HI (Heat Index), COMFA (COMfort FormulA), PET (Physiological Equivalent Temperature), and UTCI (Universal Thermal Climate Index). The most frequently applied WBGT was initially used in the military (Budd, 2008) and subsequently became a standard accepted by many professional sports-related organizations and institutes, including the National Athletic Trainers Association, the National Federation of High School Sports, the National Collegiate Athletic Association, Sports Medicine Australia, among others (Cooper et al., 2020; Schultz, Kenney, & Linden, 2014). HI, recommended by The National Weather Service (see: https://www.weather.gov/arx/heat_index), has been designed to show how intense heat and humidity can place people in hazardous scenarios on game days (Kman, Russell, Bozeman, Ehrman, & Winslow, 2007; Perron, Brady, Custalow, & Johnson, 2005). COMFA and its revision COMFA-Kid, as open architecture models based on human being's energy balance, can evaluate the thermal sensation and heat stress level for adults (Kenny, Warland, Brown, & Gillespie, 2009a, 2009b; J. Vanos, Warland, Gillespie, & Kenny, 2012) and children (Cheng, 2020; Cheng et al., 2020) in exercise. PET and UTCI have been used to assess the heat stress in the Gothenburg half-marathon (Thorsson et al., 2020).

People's heat stress in sports is affected by physical activity intensity, local weather, as well as the microclimate condition which can be altered through design interventions (Vanos et al., 2017). Sports field represents one of the many spaces purposed for outdoor physical activity, yet many lack shade. Artificial turf (AT) and natural turf (NT) are the main sports field categories. In comparison, AT has increasingly replaced NT due to lower maintenance costs, easier maintenance, durable playing surface, and less lingering playability problems after inclement weather (Jim, 2017). However, in recent years, many researchers have assessed the environmental, health, and biodiversity impact of AT, such as its chemical emissions, high surface temperature, knee injury risk, among others (Adamson & Fresenburg, 2005; Francis, 2018; Ginsberg et al., 2011; Loughran et al., 2019). The VCCCAR (The Victorian Centre for Climate Change Adaptation Research) considered AT as "not all green infrastructure is 'green' " because "you can paint it green, but that doesn't make it sustainable" (Englart, 2021).

To investigate turf material's effect on people's heat stress exposure, previous studies conducted comprehensive field measurements to compare AT and NT's thermal performance on the microenvironment. Jim (2016) conducted an on-site measurement in humid-subtropical Hong Kong. He reported that the AT-NT differences in air temperature (Ta) at pedestrian level, ground surface temperature (GST), net shortwave radiation, and net longwave radiation were respectively 1.1°C, 37.6°C, -144.7 W/m^2, and 152.4 W/m^2 on a hot sunny summer day with a clear sky. Devitt, Young, Baghzouz, Bird, and Devittl (2007) recorded the Ta, GST, shortwave radiation (SR), spectral reflectance of six turf materials including AT and NT, and found that the AT-NT difference in Ta was limited, but the AT-NT difference in GST reached 38.4°C. As reported by several studies, GST is one of the most considerable microclimate differences between AT and NT, ranging from around 30 to 60°C (Adamson & Fresenburg, 2005; Buskirk, McLaughlin, & Loomis, 1971; Devitt et al., 2007). The AT-NT difference in thermal effect is mainly due to their specific thermodynamic properties, which affect their GST (and thus emitted longwave radiation towards field users), thermal admittance, surface moisture, and surrounding Ta (Guyer, 2020). On the one hand, as a living system, NT often has 70% moisture by weight, imparting the ability to cool itself effectively through evapotranspiration and confining the diurnal GST within a limited range (Devitt et al., 2007). On the other hand, NT tends to reflect more shortwave radiation to field users due to its high surface albedo (Jim, 2016). In contrast, due to low specific heat, limited moisture and thermal storage capacity, and scanty evapotranspiration, AT can experience fast warming and cooling with little time lag and a notably wider diurnal GST range (Jim, 2017).

Despite previous empirical research about AT, NT and their thermal-effect difference, two issues of conceptual and practical significance have remained inadequately understood:

(1) So far, most AT-NT-related research have focused on the turf material's overall thermal performance, attempting to portray the difference in microclimate parameters, such as ground surface temperature, air temperature, reflected shortwave and longwave radiation. Detailed research focused on field users' heat stress is still lacking, especially for humid subtropical and tropical climate regions. The key knowledge gaps can be highlighted by targeted research questions such as "how does each turf material affect the energy fluxes of a person when exercising on it?" and "how much does turf material affect human convection, evaporation, and absorbed radiation fluxes, respectively?". We hope to make a detailed comparison of AT and NT's human-biometeorological effects.
(2) Sports fields are public infrastructures used by different age groups for various physical activities. The plight of children and the young as heat vulnerable groups suffering from severe heat stress in sports needs special attention. However, little is known whether the commonly used heat stress indicators can appropriately assess heat stress for children and the young in sports. The characteristics and suitability, i.e., how, why, when, and for whom and under what conditions a model could be applied (Grundstein & Vanos, 2020), deserve to be analyzed systematically and critically. Furthermore, in comparing the heat stress level at AT and NT using selected indices, it is worthwhile to investigate whether they are comprehensive or detailed enough to tell the difference between AT and NT's human-biometeorological effects with reference to different age groups and different physical activity intensities.

To solve these pending issues, this study analyzed the human-biometeorological effect of artificial and natural turf sports fields in a hot-humid climate region (Hong Kong). With a comprehensive field measurement campaign under three summer weather conditions (sunny, cloudy, and overcast), three heat stress indicators (HI, WBGT, COMFA), three age groups (children, young athletes, and adults), and two physical activities (playing soccer games and walking) were applied for in-depth heat stress analysis. Particularly, a novel COMFA revision for young athletes in sports was applied here. This study compared the heat stress level and duration experienced by field users at AT and NT. The findings could provide targeted suggestions for urban designers, sports field managers, and policy-makers who want to improve the outdoor sports thermal condition and reduce the morbidity of exertional heat illness.

2. Methods

2.1. Collecting microclimatic data

2.1.1. Study area

The field measurement was conducted in Hong Kong, a high-density city located at the south China coast at longitude of 113° E and latitude 22° N near the Tropic of Cancer. As a typical city in the humid subtropical climate region (Cfa), according to Köppen-Geiger climate classification (Peel, Finlayson, & McMahon, 2007), the weather is mainly regulated by the large-scale Asian monsoon system. It has a hot and humid summer from May to September, with a 28.5°C mean air temperature and around 80% relative humidity (Cheung & Jim, 2018). The daily maximum air temperature usually exceeds 31°C in the afternoon (Chan, 2011).

The experiment sites were conducted in two adjacent sports fields, namely an artificial turf (AT) and a natural turf (NT) in the sports center of the University of Hong Kong, at a coastal plot on the west side of the Hong Kong Island. They were both open fields with a sky view factor over 90%, minimizing the thermal and ventilation influence from surrounding objects (e.g., buildings and trees). The AT was a third-generation product, with detailed descriptions in papers (Fleming, Watts, & Forrester, 2020; Francis, 2018; Jim, 2016). The NT was covered with *Cynodon dactylon* (Bermudagrass) nurtured by local tropical soil. The study area locations, turf layouts and photographs of the microclimatic monitoring equipment are shown in Fig. 1.

2.1.2. Measurement of microclimate parameters

The field measurement was carried out in summer, under three sky conditions: sunny (4 Aug and 5-6 July, 2014), cloudy (5 and 12 Aug, 2014), and overcast (7 July, 2014). The sky condition classification criteria in this study (Table 1) was combined with the classification criteria of Hong Kong Observatory (see: https://www.hko.gov.hk/en/wxinfo/currwx/flw_description/flw.htm) and National Weather Service (see: https://www.weather.gov/bgm/forecast_terms). The measuring points were situated at the field center with two sets of replicated instruments. The manufacturers, brands and accuracy of the measuring instruments are listed in Table 2. The field measurement lasted 24 hours each day. The microclimate variables were sampled at an interval of 15 minutes. To represent the microclimate conditions at the pedestrian level, the sensors were placed at a height of 1.5 m. The shortwave and longwave radiation environment was measured by a CNR4 net radiometer with two upper hemisphere sensors for shortwave radiation downward ($SR_{downward}$) and longwave radiation downward ($LR_{downwad}$); and two lower hemisphere sensors for shortwave radiation upward (SR_{upward}) and longwave radiation upward (LR_{upward}). The pertinent data of the collected microclimate parameters are showed in Appendix A.

2.2. Estimating heat stress potential

The heat stress potential was assessed by three heat stress indices, namely HI, WBGT, and COMFA, for two reasons. First, they have been widely used in environmental heat exposure estimation and heat stress risk assessment (Cheng et al., 2020; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Kim, Ha, & Park, 2006; Pfautsch et al., 2020; Smoyer, Rainham, & Hewko, 2000). Second, they have been applied to evaluate the heat stress level in sports (Koon, Rochester, & Howard, 1972; Ramsey, 1982; Walker, 2010).

2.2.1. HI (heat index)

HI, also known as the apparent temperature, is what the temperature feels like to the human body when relative humidity is combined with the air temperature. The equation is (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016):

$$\begin{aligned}\mathrm{HI} = & -8.784695 + 1.61139411 \cdot T_a + 2.338549 \cdot RH - 0.14611605 \cdot T_a \cdot RH \\ & - 1.2308094 \cdot 10^{-2} \cdot {T_a}^2 - 1.6424828 \cdot 10^{-2} \cdot RH^2 + 2.211732 \cdot 10^{-3} \cdot {T_a}^2 \cdot RH \\ & + 7.2546 \cdot 10^{-4} \cdot T_a \cdot RH^2 - 3.582 \cdot 10^{-6} \cdot {T_a}^2 \cdot RH^2 \end{aligned} \tag{1}$$

where T_a is the air temperature (°C), and RH is the relative humidity (%).

2.2.2. WBGT (wet bulb globe temperature)

WBGT has long been applied in sports and recommended by the International Organization for Standardization (ISO) (Brocherie & Millet, 2015; Coccolo et al., 2016; Parsons, 2006) for its well-known benefits, including simple measurement and calculation and multiple weather variable integration (A. Grundstein & Vanos, 2020). WBGT for the outdoor environment is defined as (Coccolo et al., 2016):

$$\mathrm{WBGT} = 0.7T_w + 0.2T_g + 0.1T_a \tag{2}$$

where T_w is the natural wet-bulb temperature (°C), T_g is the black globe temperature (°C), and T_a is the air temperature (°C).

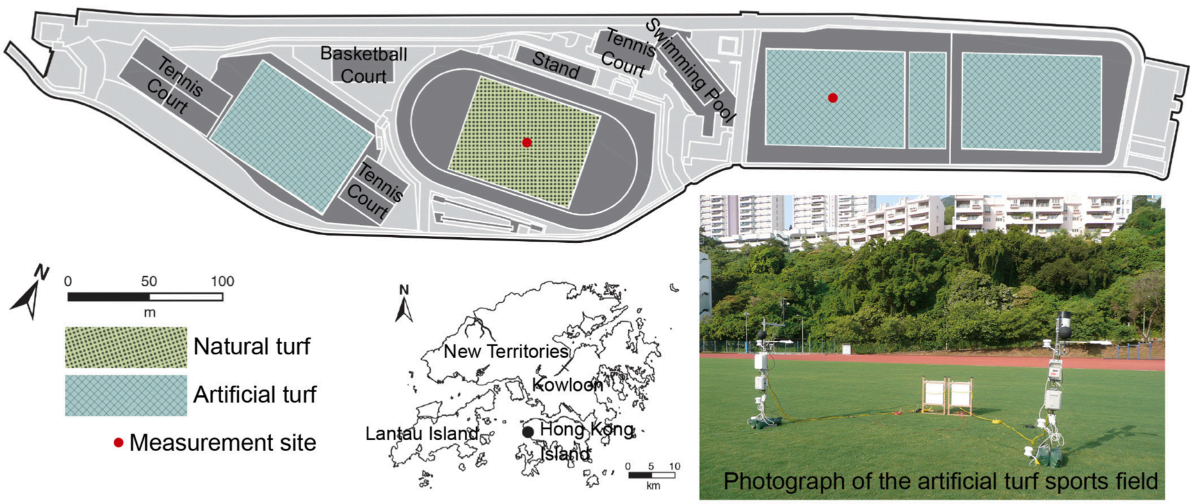

Fig. 1. The locations and photographs of the selected sports fields in the study area.

Table 1
The sky condition classification criteria

Sky condition	Opaque cloud coverage
Sunny	1/8 or less
Cloudy	1/8 to 8/8
Overcast	The whole sky is covered completely by a continuous, thick and opaque cloud layer

Table 2
The measured parameters, and the technical traits and accuracy of the sensors deployed in the microclimatic monitoring of the turf sports fields.

Parameter	Sensor type, brand, model, and manufacturer	Accuracy
Air temperature	Hobo S-THB (Thermistor), Bourne, MA, USA	±0.2°C
Relative humidity	Hobo S-THB (Thermistor), Bourne, MA, USA	±2.5 %
Wind speed	Hobo S-WCA (Cup anemometer), Bourne, MA, USA	±0.5 m/s
Ground surface temperature	Apogee SI-111 (Infrared radiometer), Logan, UT, USA	±0.2°C
Wet-bulb temperature	ESU121 (Thermistor), LSI LASTEM, Milan, Italy	± 0.15°C
Globe temperature	LSI EST131(Globe thermometric probe), Settala, Milan, Italy	±0.15°C
Solar radiation (upward and downward)	Kipp & Zonen CNR4 (Net radiometer), Delft, the Netherlands	<5% W/m^2
Terrestrial radiation (upward and downward)	Kipp & Zonen CNR4 (Net radiometer), Delft, the Netherlands	<5% W/m^2

2.2.3. COMFA (COMfort FormulA)

COMFA is based on heat budget equations that describe more completely the flows of energy to and from a person in any landscape (Brown & Gillespie, 1995). The basic COMFA equation is (Brown & Gillespie, 1995):

$$\text{Budget} = M + R_{abs} - CONV - EVAP - TR_{emitted} \tag{3}$$

where M is the metabolic energy for heating up the body (W/m^2), R_{abs} is the absorbed shortwave and terrestrial (longwave) radiation (W/m^2), CONV is the sensible convective heat exchange (W/m^2), EVAP is the evaporative heat loss (W/m^2), and $TR_{emitted}$ is the emitted terrestrial (longwave) radiation (W/m^2). R_{abs}, the total radiation received by a person, includes two components: the total absorbed shortwave radiation (K_{abs}), and the total absorbed terrestrial (longwave) radiation (L_{abs}). K_{abs} is estimated by summing all the sources of shortwave radiation received by a person, including shortwave radiation received directly, diffuse sky radiation received directly, and radiation reflected by the ground (Brown & Gillespie, 1995). Only the global radiation was measured because of the lack of equipment in this study, diffuse radiation was estimated as 10% of global radiation on sunny days and as 100% on overcast days, referring to Brown and Gillespie (1995). L_{abs} is estimated by summing all the sources of terrestrial (longwave) radiation received by a person, including the terrestrial (longwave) radiation from the sky (estimated from air temperature and sky view factor) and ground hemisphere (estimated from the ground surface temperature). $TR_{emitted}$ is estimated by the surface temperature of a person, which is estimated from the air temperature and a person's metabolic heat (Brown & Gillespie, 1995).

Detailed equations for each COMFA component can be found in Brown and Gillespie (1995). The measured microclimate variables were used in the calculation. This study applied an Excel calculation file published on the COMFA development team's website to obtain the original COMFA values for adults without professional physical training (see: https://research.arch.tamu.edu/microclimatic-design/COMFA/index.html). Since each component can be adjusted individually in that calculation file, COMFA can be adjusted to different revisions to accommodate different targeted objects.

This study applied one of the COMFA revisions entitled COMFA-Kid to calculate the energy budget of children without professional physical training. COMFA-Kid is targeted at children, revised from the original COMFA model with the same main equation (Cheng, 2020; Cheng & Brown, 2020). The notable differences between COMFA and COMFA-Kid are in M, CONV, and EVAP, due to differences between children and adults regarding surface-area-to-mass ratio, metabolic rate, skin temperature during exercise, and sweat rate (Cheng, 2020). The detailed equations of COMFA-Kid can be found in Cheng (2020).

As one of the innovations, this study developed a COMFA revision particularly for young athletes in sports, using a revised M calculation method and considering the metabolic rate difference between a normal young man and a young athlete.

$$M = (1 - f)M^* \tag{4}$$

$$f = 0.150 - 0.0173e - 0.0014(Ta) \tag{5}$$

where M^* is the total metabolic heat generated by a person (W/m^2), f is a correction for the heat loss consumed through breathing, Ta is the air temperature (°C), e is the saturation vapor pressure at air temperature.

M* is based on the activity level and MET for different activities. MET is the unit that divides a certain activity energy expenditure by the resting metabolic rate. By multiplying the RMR and MET rate, the activity heat production can be calculated (Cheng & Brown, 2020). The RMR of male athletes is based on the Harris-Benedict equation (Harris & Benedict, 1918), and the RMR of female athletes is based on the Cunningham equation (Cunningham, 1980), with accuracy and appropriateness for athletes evaluated by Jagim et al. (2018):

$$\text{RMR for male athletes} = 66.47 + 13.75\text{BM} + 5\text{H} - 6.76\text{A} \quad (6)$$

$$\text{RMR for female athletes} = 500 + 22\text{LBM} \quad (7)$$

$$\text{Female LBM} = (69.8 - 0.26 \times \text{BM} - 0.15\text{A}) \times \text{BM} + 73.2 \quad (8)$$

where RMR is the resting metabolic rate (kcal/d), BM is the body mass (kg), H is the body height (cm), A is the age, and LBM is the lean body mass (kg).

The input values for the three age groups' energy budget calculations are listed in Table 3. The children group used the COMFA-Kid model. The young athlete and adult groups respectively used the M-revised and the original COMFA model. COMFA*, which was revised for high metabolic rate (> 400 W/m^2). This high rate was not adopted in our study because almost all the metabolic rate values in this study were lower than 400 W/m^2, hence it was not necessary to revise its tissue resistance, relative air velocity, skin temperature, clothing, and vapor resistance calculation methods (Kenny et al., 2009b). In this study, the children group was set as a 7-year-old boy because seven is the youngest in the COMFA-kid verified age range (Cheng, 2020). The young athlete group was set as an 18-year-old male athlete, which is in the range of the youth's physical activity compendium (Butte et al., 2018). The adult group was set as a 30-year-old man, based on the "average adult" from the ISO standard (ASHRAE, 2004). The body height and weight of the children and young athlete groups met the growth standard from Hong Kong Growth Survey in 1993 (see, https://www.cuhk.edu.hk/proj/growthstd/index.htm), using the 50th percentile value. The adult group's body height and weight were set based on the ISO standard (ASHRAE, 2004). The body surface area was calculated from published data (Haycock, Schwartz, & Wisotsky, 1978). The children, young athlete, and adult groups' RMR were respectively calculated from published information (Cheng, 2020); (Jagim et al., 2018); (Frankenfield, Roth-Yousey, Compher, & Group, 2005). For soccer game's energy expenditure, 7.7 MET was set for children (Butte et al., 2018), 8.7 MET for young athletes (Butte et al., 2018), and 7.0 MET for adults (Ridley & Olds, 2008). For walking (2 mph, equivalent to 3.22 km/h) energy expenditure, 2.8 MET was set for children (Butte et al., 2018), 3.4 MET for young athletes (Butte et al., 2018), and 2.5 MET for adults (Ainsworth et al., 2000).

Table 3
The input values for COMFA metabolic heat calculations.

Input variable	Children	Young athletes	Adults
Age (year)	7	18	30
Weight (kg)	22	60	70
Height (cm)	120	170	175
Body surface area (m^2)	0.85	1.68	1.84
Resting metabolic rate (W/m^2)	46.98	46.67	43.41
Soccer game energy expenditure (MET)	7.7	8.7	7.0
Soccer game energy expenditure (W/m^2)	361.75	406.03	303.87
Walking (2 mph[a]) energy expenditure (MET)	2.8	3.4	2.5
Walking (2 mph[a]) energy expenditure (W/m^2)	131.54	158.68	108.53

[a] 2 mph is equivalent to 3.22 km/h. The average human walking speed is 3.1 mph or 5 km/h.

2.2.4. Heat stress scale and categories

Table 4 explains the categories of the heat stress scale, their corresponding possible heat disorders, and activity guidelines. The HI heat stress scale, which for people accustomed to the heat, was adopted in this study (Harlan et al., 2006). The COMFA heat stress scale was estimated from the HI heat stress scale using an Energy budget – HI prediction model (Energy budget=5.58 × HI-381.82, R^2=0.86) (Harlan et al., 2006). This approach has also been applied in a previous COMFA-related study (Cheng et al., 2020). The WBGT heat stress scale, which targets hot regions, was adopted in this study (Grundstein, Williams, Phan, & Cooper, 2015). The activity guidelines were based on the *Practice Policy for Heat and Humidity* from the Georgia High School Association (2020). Its recommendations were based on the corresponding WBGT heat stress categories (Grundstein et al., 2015).

2.3. Determining analysis period

This study assessed the opening hour of all the soccer pitches in Hong Kong to determine the main analysis period. From the sports facility websites of the government's Leisure and Cultural Services Department and ten universities, the opening hours of 278 soccer pitches were counted (Fig. 2), including 193 free outdoor soccer pitches, 58 fee-charging soccer pitches, 15 sports grounds, and 12 in-campus soccer pitches. The results showed that about 70% of soccer pitches open at 0700 h and close at 2300 h. Therefore, we extracted the data in this period for the main analysis. Moreover, the Hong Kong Observatory indicated sunrise at about 0600 h and sunset at 1900 h in summer. Therefore, we used 1900 h to demarcate daytime (0700-1900 h) and nighttime data (1900-2300 h).

3. Results

3.1. HI

The HI values in different weather conditions are displayed in Fig. 3. The AT and NT curves demonstrated a consistent pattern, nearly overlapping in nighttime and slightly deviating from each other in the daytime. Table 5 summarizes the pertinent data of HI values. In the daytime, the highest average and maximum HI value at both turfs occurred on sunny days, followed by cloudy days and the overcast day. On sunny days, NT expressed a wider diurnal amplitude than AT, and NT registered a higher HI than AT from about noon to early afternoon. On cloudy days, the NT and AT curves tended to converge.

The average HI was 42.53°C at AT and 42.37°C at NT in sunny daytime. The maximum HI values respectively reached 48.45°C at AT and 50.83°C at NT, at about 1500 h on sunny days. The HI values on sunny days were confined to "Extreme caution" and "Danger" heat stress zones except for short periods after dawn and after sunset. The duration of the "Danger" rating declined notably on cloudy days and more on the overcast day. On cloudy days, the HI scores concentrated in "Caution" and "Extreme caution" categories, with some periods shooting into the "Danger" zone. The overcast day was dominated by an "Extreme caution" rating. Except for a short moment in cloudy nighttime, "Safe" grading was conspicuously absent.

For the AT-NT difference in HI, the maximum index reached 7.80°C at about 1000 h on sunny days. Although the instantaneous AT-NT difference in HI was considerable, the average daytime difference was not notable, at only 0.16°C on sunny days, 0.11°C on cloudy days and 0.81°C on the overcast day. Moreover, the HI value of AT was not always higher than NT: at about 1400 h on sunny days, NT was 5.59°C above AT. In the nighttime, the AT-NT difference was subdued, at 0.17°C, -0.07°C and 0.26°C respectively for sunny, cloudy, and overcast scenarios.

Fig. 4. displays the percentage time distribution at each heat stress level in the daytime. In most sunny daytime, both AT and NT attained either "Extreme caution" or "Danger" levels. People would experience

Table 4
The categories of the heat stress scale, and corresponding possible heat disorders, threshold and range of three heat stress indices, and recommended activity guidelines.

Heat stress category	Heat disorders (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006)	HI (Harlan et al., 2006)	WBGT (Grundstein, Williams, Phan, & Cooper, 2015)	COMFA for children, young athletes, adults (Harlan et al., 2006)	Activity guidelines (GHSA, 2020)
Safe	-	<26.7°C	<27.8°C	<60 W/m^2	Normal activities - Provide at least three separate rest breaks each hour with a minimum duration of 3 min each during the workout.
Caution	Fatigue possible; discomfort	26.7-31.7°C[a]	27.9-30.5°C	60-120 W/m^2	Provide at least three separate rest breaks each hour with a minimum duration of 4 min each.
Extreme caution	Sunstroke, heat cramps, heat exhaustion possible	32.2-40.0°C[a]	30.6-32.2°C	121-200 W/m^2	The maximum practice time is 2 h.
Danger	Sunstroke, heat cramps, heat exhaustion likely, and heatstroke possible	40.6-53.9°C[a]	32.3-33.3°C	201-339 W/m^2	The maximum practice time is 1 h.
Extreme danger	Sunstroke and heatstroke highly likely	>54.4°C	>33.4°C	>340 W/m^2	No outdoor workouts. Delay practice until a cooler WBGT level is reached.

[a] When collecting the percentage distribution of time at each heat stress level, the HI scale was adjusted into an overlapped range as: Safe (<26.7°C); Caution (26.7-32.2°C); Extreme caution (32.2-40.6°C); Danger (40.6-53.9°C); Extreme danger (>54.4°C).

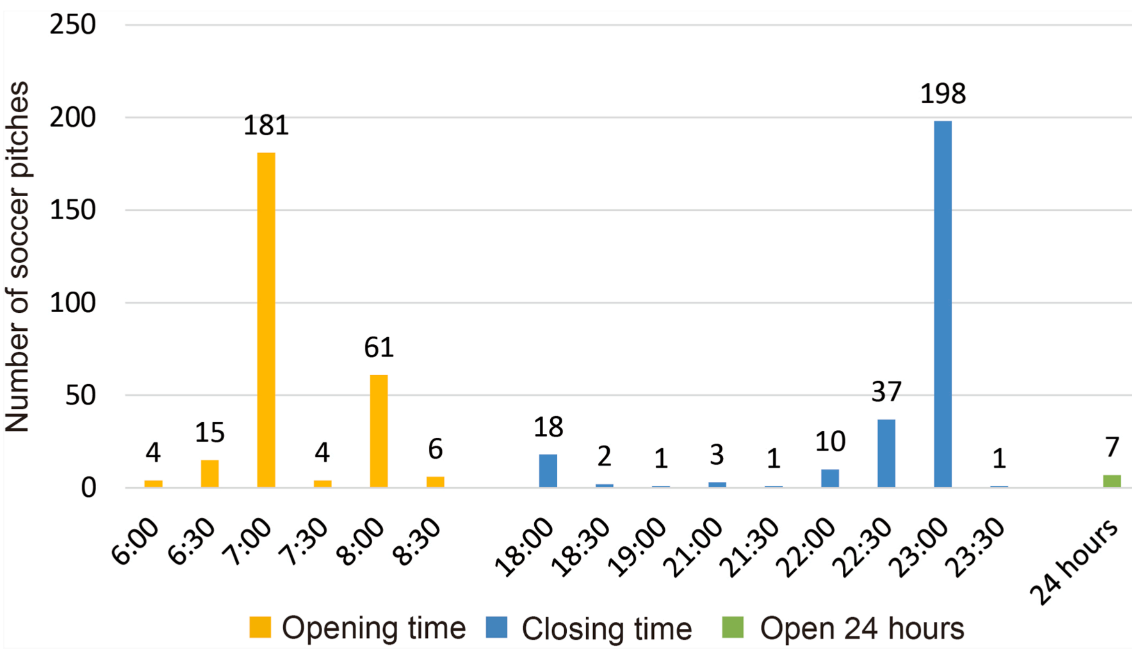

Fig. 2. The frequency distribution of the opening and closing times of Hong Kong soccer pitches.

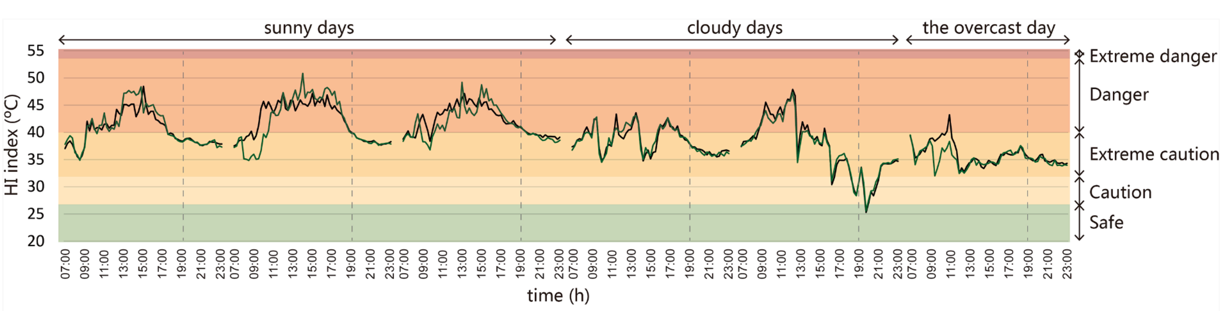

Fig. 3. HI values in different weather conditions in relation to heat stress categories.

Table 5
The pertinent HI data in different weather conditions.

Weather condition	Time period	Data type	Artificial turf (AT) (°C)	Natural turf (NT) (°C)	AT-NT (°C)
Sunny days	Daytime	Max	48.45	50.83	7.80
		Min	35.04	34.84	-5.59
		Mean	42.53	42.37	0.16
	Nighttime	Max	40.52	40.49	1.07
		Min	37.57	37.19	-0.43
		Mean	38.67	38.49	0.17
Cloudy days	Daytime	Max	47.89	47.34	2.53
		Min	28.40	28.33	-2.02
		Mean	39.13	39.03	0.11
	Nighttime	Max	37.33	37.17	1.01
		Min	25.30	25.55	-1.18
		Mean	34.13	34.19	-0.07
The overcast day	Daytime	Max	43.24	39.51	6.38
		Min	32.49	32.00	-0.82
		Mean	36.30	35.49	0.81
	Nighttime	Max	35.94	35.61	0.88
		Min	34.11	33.83	-0.49
		Mean	34.80	34.54	0.26

the longest duration in “Danger” on sunny days, followed by cloudy days and the overcast day. The turf materials slightly affected the heat stress duration. Sunny days showed a notable AT-NT difference, with AT recording 5.44% longer “Danger” duration than NT. On the overcast day, NT had 2.04% less “Danger” duration and 2.04% more “Caution” duration than AT. NT did not always have a shorter “Danger” duration than AT in daytime, for example, for cloudy days, NT displayed a similar “Danger” duration and a slightly longer “Extreme caution” (1.42%) than AT.

3.2. WBGT

Fig. 5. shows the WBGT values in different weather conditions, with consistent trends of AT and NT. Table 6 displays the pertinent data of WBGT. In the daytime, the average and maximum WBGT values at both turfs followed a descending sequence: sunny days > cloudy days > overcast day. The average WBGT was respectively 31.27°C at AT and 31.42°C at NT on sunny days, 29.44°C at AT and 29.47°C at NT on cloudy days, and 27.84°C at AT and 27.77°C at NT on the overcast day. The maximum WBGT attained 34.81°C at AT and 34.39°C at NT on sunny days, at about 1400–1500 h.

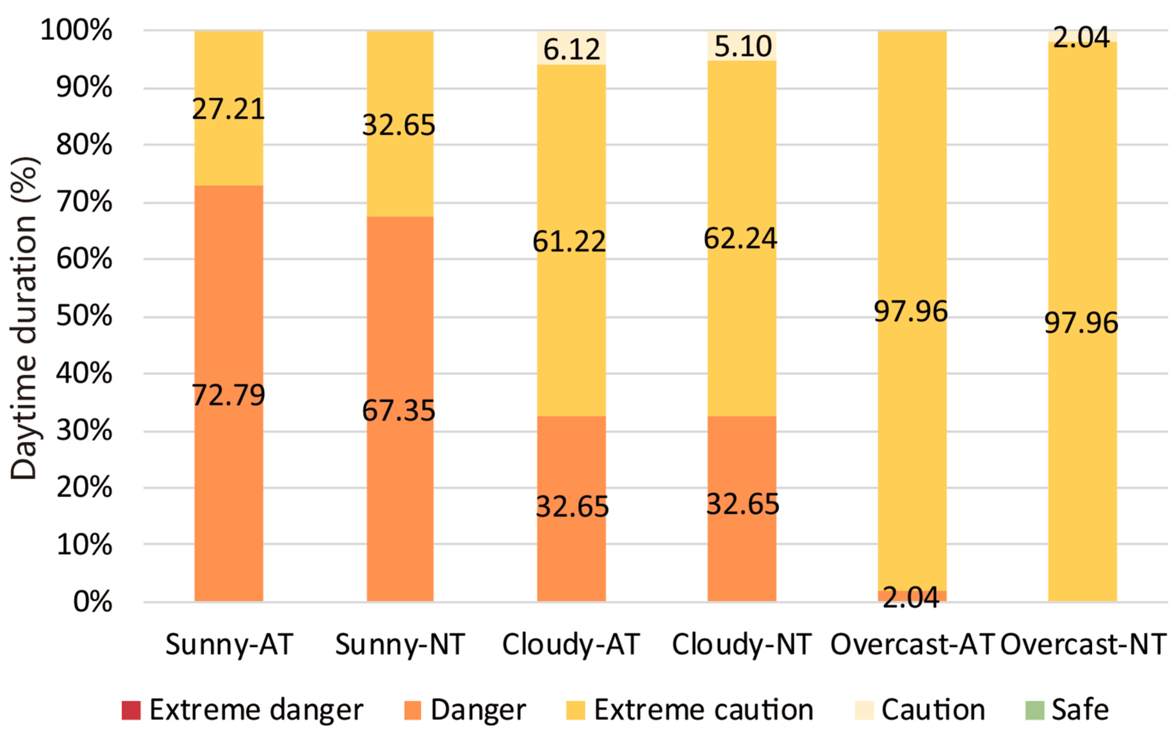

Fig. 4. The percentage distribution of time at each heat stress level (HI) in daytime in different weather conditions.

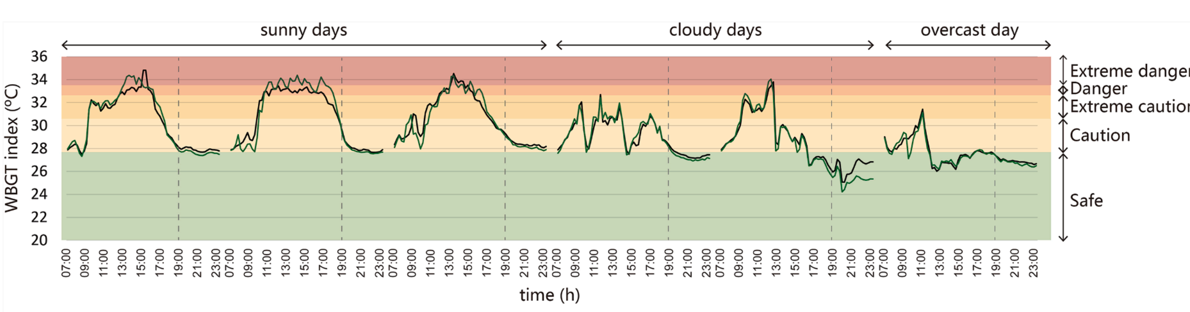

Fig. 5. WBGT values in different weather conditions in relation to heat stress categories.

Table 6
The pertinent WBGT data in different weather conditions.

Weather condition	Time period	Data type	Artificial turf (AT) (°C)	Natural turf (NT) (°C)	AT-NT (°C)
Sunny days	Daytime	Max	34.81	34.39	1.80
		Min	27.50	27.31	-1.55
		Mean	31.27	31.42	-0.14
	Nighttime	Max	28.72	28.68	0.37
		Min	27.66	27.39	0.04
		Mean	28.04	27.82	0.22
Cloudy days	Daytime	Max	33.80	34.04	0.99
		Min	25.95	25.48	-1.06
		Mean	29.44	29.47	-0.02
	Nighttime	Max	27.77	27.54	1.55
		Min	25.08	24.22	0.15
		Mean	26.90	26.21	0.69
The overcast day	Daytime	Max	31.42	31.14	1.73
		Min	26.03	26.22	-0.51
		Mean	27.84	27.77	0.07
	Nighttime	Max	27.09	27.03	0.34
		Min	26.61	26.39	0.03
		Mean	26.85	26.69	0.16

For the AT-NT difference in WBGT, the maximum attained 1.80°C on sunny days, 0.99°C on cloudy days, and 1.73°C on the overcast day. However, the average AT-NT difference was limited in the daytime, with negative values on sunny and cloudy days (-0.14°C and -0.02°C, respectively) and positive only on the overcast day (0.07°C).

The "Caution" and "Extreme caution" zones dominated all the sampled days. The "Danger" rating was principally registered by sunny daytime, occurring mainly from late morning to late afternoon. Cloudy days recorded only a brief "Danger" episode around noontime, and the overcast day had none. On sunny daytime, both AT and NT extended into the "Danger" zone in the late morning and afternoon, but the duration was shorter than the HI assessment. On cloudy days, only a brief period was rated as "Danger", and none was recorded on the overcast day. The "Safe" assessment was expressed by cloudy days and the overcast day in the late afternoon and nighttime.

Fig. 6. displays the percentage distribution of time at each heat stress level in the daytime. On sunny days, people experienced a slightly longer duration in the aggregated "Extreme danger", "Danger", and "Extreme caution" conditions at AT than NT. However, NT registered 16% longer "Extreme danger" duration than AT. Both turfs recorded a very brief period of "Safe" rating. On cloudy days and the overcast day, people experienced a long duration respectively in "Caution" and "Safe" conditions. For all sampled days, people at NT would experience a longer "Safe" but also a longer "Extreme danger" heat stress condition. At NT, people would be stressed 16% longer under "Extreme danger" conditions on sunny days and be stressed 1% and 5% longer under "Danger" and "Extreme caution" conditions on cloudy days.

3.3. COMFA

The energy budget of children, young athletes, and adults playing soccer games and walking are respectively displayed in Fig. 7. The pertinent data of the energy budget are shown in Appendix B. The more energetic soccer game pushed all scores into the "Extreme danger" and "Danger" zones on all sampled days. The "Extreme danger" rating was expressed overwhelmingly in sunny daytime and less so in cloudy daytime, but afflicted even the overcast day. For the gentle walking, the sunny daytime registered mainly "Extreme danger" and "Danger" scores from morning to afternoon. Cloudy days had brief periods getting into the "Extreme danger" category, whereas the overcast day had none.

The average energy budget of the three age groups demonstrated a descending sequence: young athletes > children > adults, in both physical activities and turf materials. In the daytime, the maximum energy budget occurred in children, followed by young athletes and adults. For physical activities, the energy budget of playing soccer was considerably larger than walking in all age groups. For weather conditions, the energy budget on sunny days was the largest, followed by cloudy days and the overcast day in the daytime.

For the maximum energy budget of young athletes playing soccer games in sunny daytime, AT exceeded NT by 72.03 W/m^2. However, the energy budget at AT was not always larger than NT. At about 0800 h on sunny days, young athletes' energy budget when playing soccer games at NT could be 34.88 W/m^2 larger than AT. In the daytime, the average

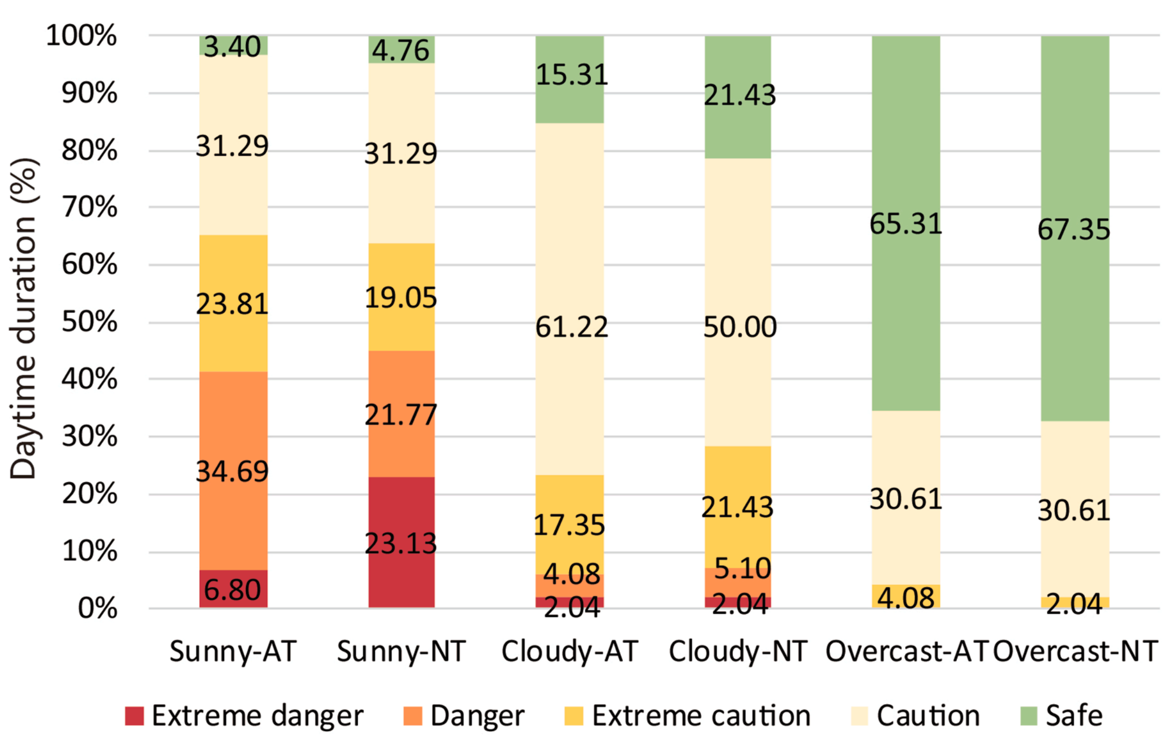

Fig. 6. The percentage distribution of time at each heat stress level (WBGT) in daytime in different weather conditions.

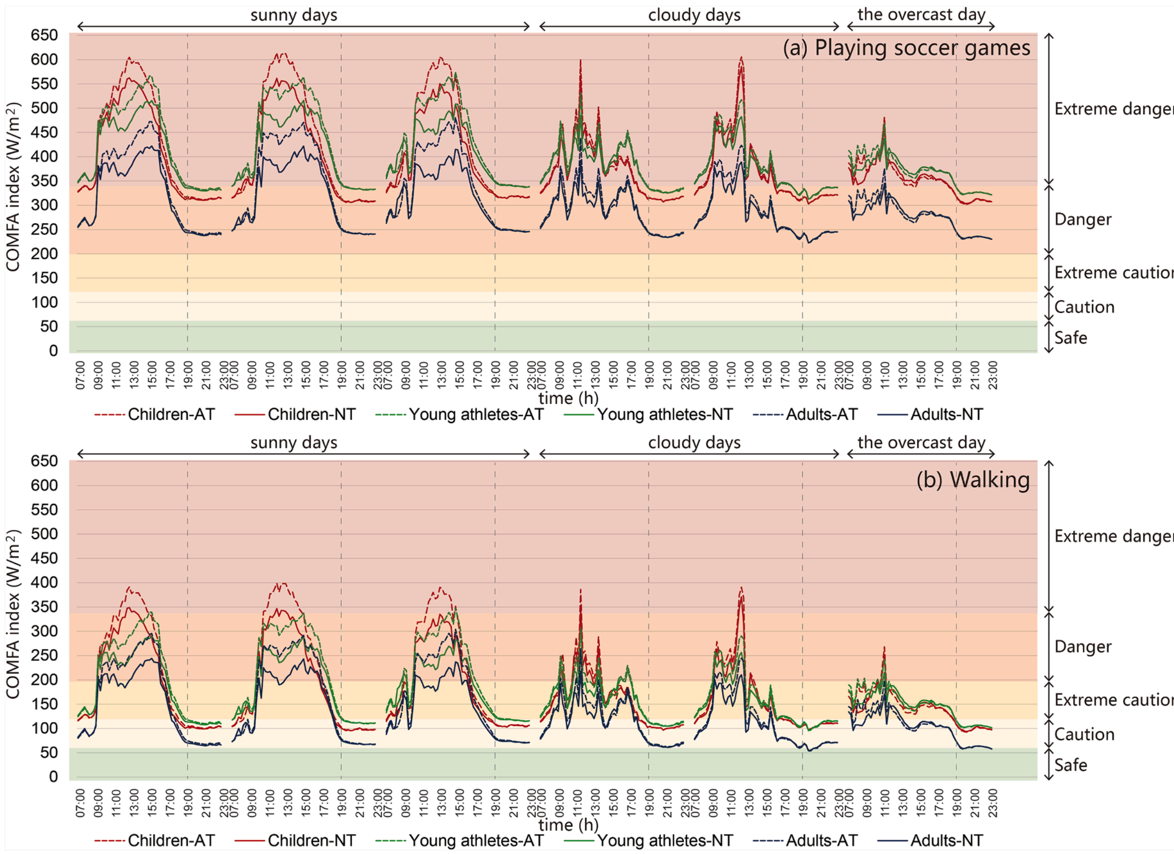

Fig. 7. The COMFA energy budget of children, young athletes, and adults in different weather conditions in relation to heat stress categories: (a) Playing soccer games, and (b) Walking (2 mph). The vertical dashed line on each sampled day at 1900 h demarcates daytime and nighttime.

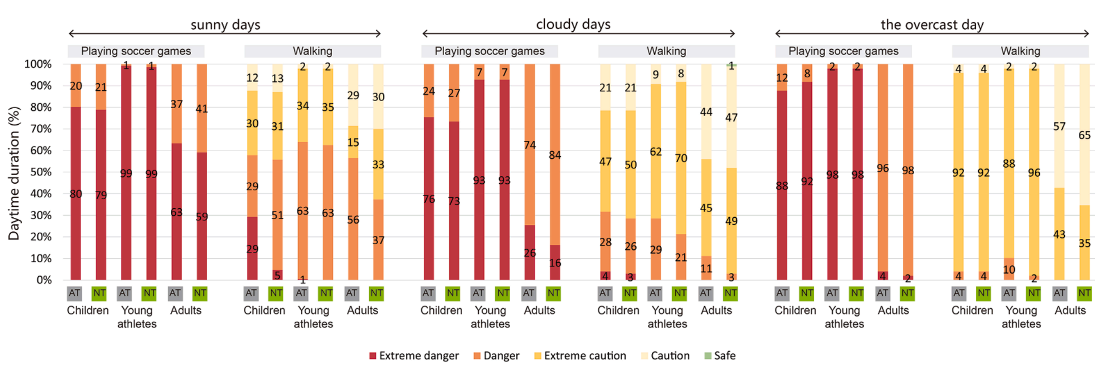

Fig. 8. The percentage distribution of time at each heat stress level (COMFA) in daytime in different weather conditions for playing soccer games and walking.

AT-NT differences were similar in all age groups and physical activities. They were markedly different among weather conditions, with AT exceeding NT by 26.95 W/m^2 on sunny days, 9.45 W/m^2 on cloudy days, and 4.68 W/m^2 on the overcast days. In the nighttime, the average AT-NT differences were notably subdued in all age groups, physical activities, and weather conditions.

Fig. 8. displays the percentage distribution of time at each heat stress level in the daytime. When playing soccer games, people would experience "Extreme danger" and "Danger" conditions most of the time, regardless of age groups, physical activities, and weather conditions. However, the difference in heat stress duration between AT and NT was limited, as AT had only less than 5% longer duration than NT in most scenarios. Even for walking, people would experience "Danger" or "Extreme caution" conditions most of the time and suffer considerably longer heat stress durations at AT than NT. On sunny days, children would experience 29% time in "Extreme danger" condition at AT, which was 24% longer than NT. Adults would suffer 56% more time in the "Danger" condition at AT, which was 19% longer than NT. On cloudy and overcast days, NT's heat stress conditions were slightly better than AT, and switching from AT to NT could reduce "Danger" duration up to 8%.

4. Discussion

4.1. *Difference in heat stress category among HI, WBGT and COMFA*

The three thermal comfort indices yielded considerably different distributions by heat stress categories. HI indicated that people were mostly at "Extreme caution" and "Danger" levels. WBGT showed people were mostly at "Extreme caution", "Caution", and "Safe" levels. COMFA results indicated that people were mostly at "Extreme danger" and "Danger" levels when playing soccer games and at "Danger", "Caution", and "Extreme caution" levels when walking. For the heat stress category results, Cheng et al. (2020) reported that HI and WBGT tended to underestimate the heat stress level in comparison with COMFA and its revision COMFA-Kid. Our findings matched this observation.

The difference in characterization of heat stress levels among HI, WBGT, and COMFA might be influenced by the thermal comfort indicators' computed absolute values vis-a-vis heat stress category standards. The former was affected by the indicator's included parameters, calculation methods and assumptions (Table 7). Brotherhood (2008) reported that heat stress estimation typically involves six factors: exercise heat production, clothing, air temperature, radiant heat from the sun and environmental surfaces, wind, and relative humidity. The first two factors are related to the physiology of the human body, and the remaining are physical ambient conditions measured by meteorological sensors. COMFA encompassing almost all the microclimate and human physiological parameters (Coccolo et al., 2016) is considered the most comprehensive and most accurate heat stress indicator in this study. In contrast, HI and WBGT consider a limited number of parameters. WBGT's equation signifies that Ta accounts for only 10% of heat stress versus humidity at 70% (Bar-Or, 1983). Therefore, Thorsson et al. (2020) reported that WBGT tends to underestimate heat stress when evaporation of sweat is restricted, e.g., in high relative humidity (RH) or low wind speed (WS) locations such as humid-subtropical Hong Kong. Ta and RH are the only input of HI. However, other microclimate and human physiological conditions were assumed to simplify the model and cannot be modified (i.e., vapor pressure, effective wind speed, body core temperature, among others) (Rothfusz, 1990).

In sports, metabolic heat is one of the critical heat stress factors for field users. In COMFA, the metabolic heat component is calculated by the resting metabolic rate and physical activity's energy expenditure, which tend to vary by age group and activity type. In contrast, the metabolic rate is not a linear factor in WBGT. Its value has to be compared with tables presented in ISO 7243, showing the corresponding scales of the defined four-class activity intensity (Coccolo et al., 2016; d'Ambrosio Alfano, Malchaire, Palella, & Riccio, 2014; Parsons, 2006). HI does not consider the metabolic rate in its equation and assumes that the metabolic output was a moderate level of 180 W/m^2, which is equivalent to the energy expenditure of walking outdoors at an average human pacing speed of 3.1 mph (5.0 km/h) (Rothfusz, 1990). Since the heat stress in playing soccer was the main target of this study (energy expenditure ranging from about 300–400 W/m^2 for different age groups), HI would have underestimated by a notable margin the heat stress because of the inordinately low assumed metabolic rate.

Clothing condition is another significant heat stress factor, which can only be modified by COMFA amongst the three indices. In COMFA, the resistance of clothing affects human convection as a function of the insulation value of clothing, the air permeability of clothing fabric, and wind velocity (Brown & Gillespie, 1995; Kenny et al., 2009a). WBGT considers clothing color (for absorptivity) in calculating globe temperature, but it is only for regular working clothes with olive drab cotton materials (d'Ambrosio Alfano et al., 2014; Parsons, 2006). HI assumes the clothing condition as long trousers and a short-sleeved shirt, with 84% coverage area (Rothfusz, 1990). Without the means to modify clothing parameters, WBGT and HI may generate inaccuracy or error in assessing heat stress.

In some calculation and measurement details, WBGT values may not be accurate enough due to the technique of measuring global temperature and the omission of relative air velocity. Brown (2019) reported that the most commonly used spherical globe thermometer was designed for the indoor environment but not appropriate for the outdoor environment because of the strongly directional outdoor radiation. Brocherie and Millet (2015) reported that the omission of relative air velocity on sports locomotion might contribute to inaccuracy in evaluating heat stress.

For the heat stress category standards and appropriateness, COMFA is more appropriate because it is based on the total heat gain and human physiological thermal reaction. The available modification can represent the energy budget differences among different age groups. In COMFA-Kid, children's physical and physiological characteristics were considered, and children-targeted equations were applied. This is important because children's different physical and physiological characteristics result in a different ability to store and dissipate heat (Cheng, 2020). For example, a 9 to 10 years old boy can have a surface-area-to-mass ratio 1.42 times of an adult man (Haycock et al., 1978). A five-year old boy's metabolic rate can be 1.38 times of a forty years old man's (Wenger, 1995). Children's higher metabolic rate (Wenger, 1995), higher body-surface-area-to-mass ratio (Haycock et al., 1978), higher skin temperature during exercise (Delamarche, Bittel, Lacour, & Flandrois, 1990), and lower capacity to sweat (Araki, Toda, Matsushita, & Tsujino, 1979), can bring higher metabolic heat and convective heat loss, and lower sensible evaporative heat loss than adults (Cheng, 2020). For young athletes, this study used athlete-targeted equations to calculate their metabolic heat.

Regarding the application scope, COMFA can be applied in different climate regions and has been applied to humid- subtropical climate regions (Lian, Liu, & Brown, 2020; Liu, Brown, Zheng, Jiang, & Zhao, 2020; Liu, Brown, Zheng, Zhang, & Zhao, 2020). HI and WBGT are categorized as "indices based on linear equations (Coccolo et al., 2016)", which define heat stress as an empirical relationship with the thermal environment (Cheng et al., 2020). Rothfusz (1990) reported that HI values are derived from a collection of equations that comprise a model, but "No true equation for the Heat Index exists". Besides, National Weather Service and Cooper et al. (2020) judged that HI values were devised for shady and light wind conditions. That is, HI's assumptions cannot represent the physiological thermal conditions of soccer players or the real-world practice conditions, and exposure to full sunshine can increase HI values by up to 15°C (see: https://www.weather.gov/safety/heat-index). For WBGT, although it has been used worldwide and applied in an international standard (ISO 7243), it is more suitable for the hot environment (Parsons, 2006) as it presents a detailed thermal scale for hot sensations and often neglects the cold ones (Coccolo et al., 2016). The WBGT category tends to underestimate the heat stress level (Cheng et al., 2020; d'Ambrosio Alfano et al., 2014) because its scale is originally based on the thermal sensation of workers and managers wearing regular working clothes while working in the field (Brocherie & Millet, 2015; d'Ambrosio Alfano et al., 2014; Parsons, 2006). It cannot represent the athletes' or children's thermal conditions accurately.

In sum, COMFA is the most comprehensive and appropriate heat stress indicator in this study. Therefore, more attention will be paid to COMFA results in the following discussion section.

Table 7
Meteorological parameters incorporated into the HI, WBGT and COMFA models (Cheng, Spengler, & Brown, 2020; Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016).

Heat stress index	Air temperature	Relative humidity	Wind speed	Solar radiation	Direct radiation	Diffuse radiation	Terrestrial radiation	Reflected radiation	Sky view factor	Metabolic rate	Clothing
HI	√	√	-	-	-	-	-	-	-	-	-
WBGT[a]	√	√	√	√	-	-	-	-	-	√	-
COMFA	√	√	√	√	√	√	√	√	√	√	√

[a] The global temperature for WBGT calculation is influenced by solar radiation and wind speed; the wet-bulb temperature is influenced by relative humidity.

4.2. AT-NT difference in heat stress duration

The difference in heat stress duration between AT and NT was slight when using HI as an indicator, with "Danger" duration of AT exceeding NT by only 5% even in sunny daytime. WBGT presented a 16% longer "Extreme danger" period at NT than AT. COMFA provided the most turf-material-sensitive indicator here, in which AT-NT difference can be successfully discriminated among age groups, physical activities, and weather conditions. The widest difference occurred in children walking in sunny daytime, during which the "Extreme danger" duration of AT exceeded NT by 24%.

The above phenomenon might echo the intrinsic sensitivity of individual indices. For COMFA, Liu, Brown, Zheng, Zhang, et al. (2020) conducted a sensitivity test and reported that the open area's human energy budget was most sensitive to LR_{upward}, followed by $SR_{downward}$ and GST. Here, the average AT-NT differences in these three variables were 95.40 W/m^2, -13.77 W/m^2, and 12.82°C in sunny daytime. The $SR_{downward}$ difference between AT and NT was limited due to their similar shortwave radiation environment, i.e., on the same days in two adjacent open fields. The AT-NT differences in LR_{upward} and GST were significant, which notably influenced the energy budget at different turf materials. Due to the Stefan–Boltzmann law, the LR_{upward} magnitude was influenced by GST, which has been one of the most significant microclimate variables in AT-NT comparison (Jim, 2016, 2017; Ramsey, 1982). As a critical heat stress factor for sports participants (Twomey, Petrass, Harvey, Otago, & Le Rossignol, 2016), numerous AT users have complained that the surface and air above it are evidently warmer than NT (Ramsey, 1982). The average GST difference between AT and NT in this study (12.82°C) was similar to the findings of Twomey et al. (2016) (11.2°C) but was lower than that of Kandelin, Krahenbuhl, and Schacht (1976) (30°C). The reported differences in thermal effect could be attributed to variations in background weather conditions, artificial turf generation (material and design), natural grass species, and irrigation regime (Twomey et al., 2016). On cloudy and overcast days, the AT-NT difference in energy budget was restrained compared to sunny days because their average AT-NT differences in GST were only 5.90°C and 2.39°C, respectively.

For HI, the smallest difference in heat stress duration was recorded between AT and NT. Its AT-NT difference in heat stress was largely affected by Ta and RH. Based on Grundstein and Cooper (2020), the Ta above AT should have been notably higher than NT due to reduced evapotranspiration and increased sensible heat transfers via convection over the surface. However, the AT-NT difference in Ta and RH was small even in sunny daytime, with an average difference of only 0.55°C Ta and -3.94% RH. This confined AT-NT difference was reasonable as explained by Brown and Gillespie (1995) that "The atmosphere is such an efficient mixer that any temperature or humidity differences that may occur are normally dissipated very quickly", and "Ta and RH normally cannot be modified significantly through landscape design".

For WBGT, our results showed that people might experience a longer "Extreme danger" condition at NT than AT, especially in sunny daytime. This phenomenon was a little different from the findings of HI, and it might be caused by two aspects: WBGT's calculation method and the heat stress classification criteria. On the one hand, the WBGT equation accords the heaviest weight to the wet-bulb temperature to exert considerable influence on the calculated index. Wet-bulb temperature is always lower than dry-bulb temperature because of evaporative cooling, mainly affected by Ta, RH, and WS. In sunny daytime, the AT-NT difference in Ta was positive most time with 0.55°C on average. However, some instantaneous Ta value at NT was slightly higher than AT (0.37°C higher on average) in the afternoon. RH at NT was always higher than AT, being 3.94% higher on average and 11.80% at maximum. AT and NT had similar WS due to their proximal locations. In sum, due to similar values of Ta and WS at AT and NT, the higher RH at NT would have suppressed evaporative cooling to bring a higher wet-bulb temperature at NT than AT.

On the other hand, regarding the heat stress classification standard, the range of the "Danger" level is relatively narrow (range of 32.2–33.3°C), making it easy for a slightly higher WBGT value at NT to go into "Extreme danger" level. In contrast, the standard range of HI's heat stress classification is much wider than WBGT (range of 40.6-53.9°C HI for the "Danger" level), rendering most of the heat experience to stay in "Danger" level. On cloudy and overcast days, the AT-NT difference in WBGT was confined. This pattern aligned with the results of Kopec (1977) and Grundstein and Cooper (2020), who compared WBGT among different surface types (including AT and NT) in a similar humid-subtropical climate and explained the phenomenon by the limited difference in microclimate variables.

4.3. AT-NT difference in the radiant-energy environment

To better understand the human-biometeorological effect of AT and NT, a breakdown has been applied for COMFA radiant energy flux components. Because the COMFA trends among different age groups and physical activities were consistent (Fig. 7.), we selected only the breakdown of the children group playing soccer games for in-depth analysis (Appendix C). In sunny daytime, a significant AT-NT difference was in the absorbed radiation domain with an average of 26.76 W/m^2 and a maximum of 64.24 W/m^2. The effect on CONV, EVAP, M, and emitted longwave radiation was determined to be quite limited (0.12 W/m^2, 4.70 W/m^2, 3.02 W/m^2, and 5.72 W/m^2 at maximum, respectively, in sunny daytime). This is because their Ta, RH and WS microclimatic factors registered a notably smaller AT-NT difference than radiation values. Correa, Ruiz, Canton, and Lesino (2012) reported that the more significant COMFA components in hot sunny conditions are typically absorbed radiation and emitted longwave radiation. However, Liu, Brown, Zheng, Zhang, et al. (2020) reported only R_{abs}, and this finding was consistent with our results.

Fig. 9. illustrates the components of the absorbed radiation flux (R_{abs}) separately. AT experienced more absorbed longwave radiation (L_{abs}) than absorbed shortwave radiation (K_{abs}). In sunny daytime, NT received more K_{abs} than AT, ranging from 34.57 to 0.39 W/m^2 with an average of 17.17 W/m^2. In our study, both AT and NT sites were adjoining open sports fields with a sky view factor of almost 1, K_{abs} was mainly influenced by SR from the sky (i.e. $SR_{downward}$) and the reflected SR from the ground surface (i.e. SR_{upward}). As mentioned in Section 4.2, the AT-NT difference in $SR_{downward}$ was very limited, so that the AT-NT difference in K_{abs} was derived from SR reflected from the ground surface. At around noon on sunny days (1100–1500 h), the AT-NT difference in reflected SR reached 113.23 W/m^2 on average, with the maximum of 146.32 W/m^2. This was because the average albedo of NT (0.23) was considerably higher than AT (0.073) (Jim, 2016; Ramsey, 1982).

AT and NT also differed considerably by L_{abs}, ranged from -4.71 W/m^2 to 107.35 W/m^2 with an average value of 17.56 W/m^2. In sunny daytime, the AT-NT difference in L_{abs} reached a maximum of 107.35 W/m^2 and an average value of 50.40 W/m^2. In COMFA, the emitted longwave radiation was calculated from the object surface temperature via the Stefan-Boltzmann law. The GST at AT was 25.81°C higher than NT in sunny daytime due to divergent turf albedo (Aoki, 2011; Jim, 2016, 2017), thus contributing to the substantial higher L_{abs} at AT. Buskirk et al. (1971) and Kandelin et al. (1976) also reported a relatively greater heat gain in synthetic turf than natural turf. The findings of this study suggested that a comparative study based on detailed analysis of the varied radiation components could further enhance our understanding of the linkage between thermal and radiation factors.

5. Conclusion

This study aimed to provide empirical evidence of the human experience of heat stress at natural and artificial turf sites in a hot-humid climate. We conducted comprehensive field measurements and applied three heat stress indicators (HI, WBGT, COMFA) to compare the human-

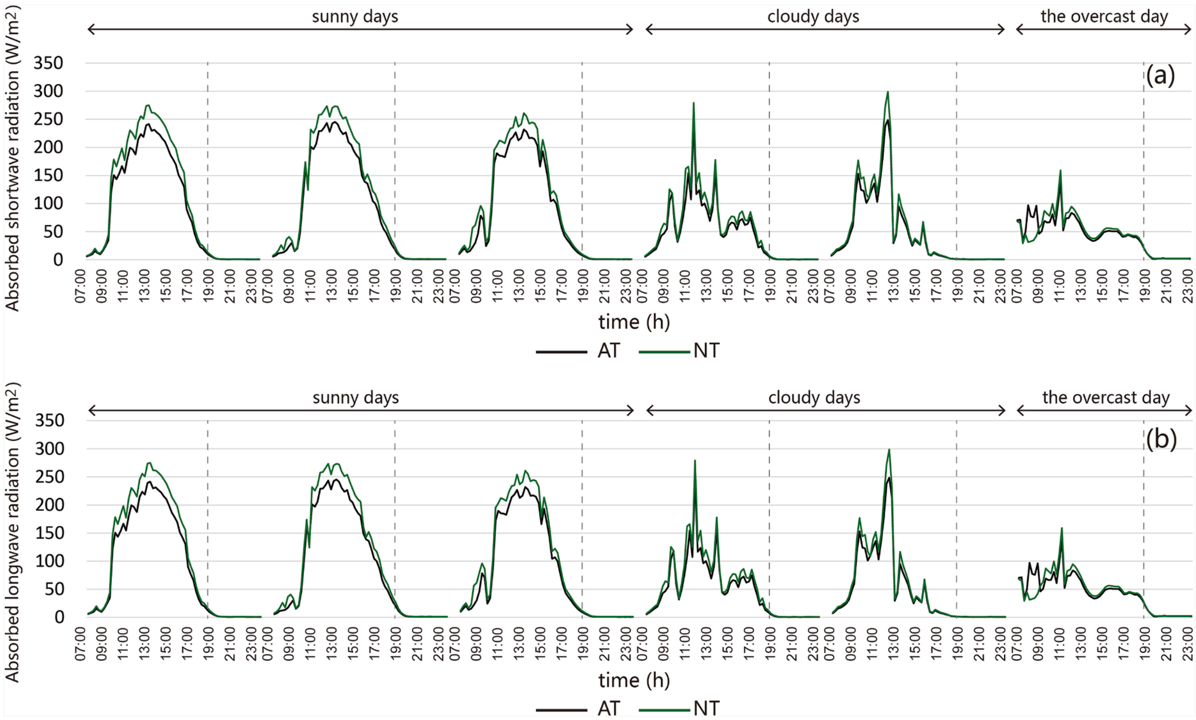

Fig. 9. Breakdown of children's absorbed radiation when playing soccer games in different weather conditions: (a) absorbed shortwave radiation (Kabs), and (b) absorbed longwave radiation (Labs).

biometeorological effect between artificial and natural turf sports fields. Three age groups (children, young athletes, and adults), two physical activities (playing soccer games and walking), and three weather conditions (sunny, cloudy, and overcast) were applied for an in-depth analysis. Special attention was paid to the difference in heat stress level and duration between artificial and natural turfs to strengthen the understanding of the connection between the turf thermal properties and human-biometeorological stress. The main conclusions are given below.

Although HI and WBGT were frequently used heat stress indicators and have been applied widely to determine outdoor playability, their appropriateness in the light of recent research advances should be reconsidered. The results showed that HI and WBGT tended to underestimate the heat stress level due to their limited inclusion of key meteorological and human physiological parameters, assumptions, and empirical calculation approach. The COMFA model, with an open architecture that can be flexibly applied to different environmental and human physiological conditions, can provide a more targeted, accurate and reliable heat stress assessment in sports.

The COMFA results indicated that people would experience a longer heat stress duration when exercising at an artificial turf sports field than a natural one. Children, the most heat vulnerable group, would have the highest energy budget than young athletes and adults. Children walking in sunny daytime may suffer from a 24% longer "Extreme danger" duration at artificial turf than natural one due to the higher ground surface temperature. The difference in human-bio meteorological effect between these two turf materials was quite limited in human convection, evaporation, metabolic heat loss, and emitted longwave radiation, but it was considerable in human absorbed radiation. For human absorbed shortwave radiation, the lower albedo of artificial turf resulted in less reflected shortwave radiation from the ground surface, thus bringing less human absorbed shortwave radiation from the lower hemisphere. In contrast, due to the lower albedo, artificial turf might induce a much higher ground surface temperature, especially around noon in sunny daytime. It could bring a much larger human absorbed longwave radiation to increase the human heat gain.

This study provides practical suggestions for urban designers, sports facility managers, and policy-makers involved in sports field applications. First, compared to an artificial turf sports field, a natural one was preferred for reducing human heat stress levels. This study suggests using natural turf sports fields, especially in kindergartens, primary schools, and sports schools, because children and young athletes have longer playing time than adults, stay closer to the high-temperature ground surface and gain more heat. A heat-safe sports field is particularly necessary for children, mainly due to their heat vulnerable physiology characteristics and the lack of self-protection awareness. Second, where artificial turf sports fields are installed, managers need to consider the effect of the elevated surface temperatures and implement management strategies to address this critical health issue in their heat policies. Such strategies could include changing the time of day play is scheduled, additional mandatory hydration and cooling breaks, and more frequent player interchanges or substitutions.

This study's findings provide an important step in understanding the human-biometeorological effect of artificial and natural turf, offering a turf material selection guideline for sports field design. The innovation of this manuscript is developing the revision of the COMFA model, revising its M calculation approach to adjust to the physiology of young athletes in sports. This study also contributes to the knowledge of the heat stress indicator appropriateness to help microclimate researchers select a more suitable indicator and provide a more accurate and reliable heat stress assessment.

This study used the COMFA model to calculate the energy budget for a theoretical person of different age groups and physical activities but lacked a real human thermal comfort survey. This might constitute one of the limitations of this study. While COMFA has a solid physical foundation and has been used in numerous human thermal comfort studies, theoretical estimation still might not fully represent the real world because of the use of "approximations". In future studies, a comprehensive human thermal comfort survey could be conducted, including detailed thermal sensation/comfort questionnaires, people usage behavior observation, and human physiological measurements.

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. The pertinent data of microclimate variables

		Daytime Sunny days		Cloudy days		The overcast day		Sunny days	Cloudy days	The overcast day	Nighttime Sunny days		Cloudy days		The overcast day		Sunny days	Cloudy days	The overcast day
		AT	NT	AT	NT	AT	NT	AT-NT			AT	NT	AT	NT	AT	NT	AT-NT		
Air temperature (°C)	Max	35.96	34.84	33.60	32.30	32.36	30.12	3.52	1.86	3.27	31.00	30.87	29.92	29.59	29.32	28.92	0.60	0.67	0.50
	Min	28.67	28.32	26.04	26.01	28.07	27.68	-1.20	-0.52	-0.25	29.94	29.54	24.97	25.07	28.32	28.15	0.03	-0.34	-0.27
	Mean	32.49	31.94	30.27	30.02	29.38	28.83	0.55	0.25	0.55	30.48	30.24	28.23	28.14	28.63	28.43	0.25	0.09	0.20
Relative humidity (%)	Max	91.40	91.90	98.20	98.80	88.30	92.20	3.00	2.00	3.40	85.90	85.50	99.50	99.70	88.20	89.60	0.90	1.20	1.60
	Min	58.40	66.60	65.40	73.20	73.00	78.40	-11.80	-7.80	-12.00	74.30	76.20	79.70	82.20	81.30	84.50	-3.80	-4.50	-3.20
	Mean	72.17	76.11	82.58	84.81	81.99	85.57	-3.94	-2.23	-3.58	78.38	80.35	90.03	91.42	85.39	87.07	-1.98	-1.40	-1.68
Wind speed (m/s)	Max	1.30	1.30	1.48	1.48	1.67	1.67	0.00	0.00	0.00	1.48	1.48	2.04	2.04	1.11	1.11	0.00	0.00	0.00
	Min	0.00	0.00	0.00	0.00	0.19	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.19	0.00	0.00	0.00
	Mean	0.47	0.47	0.37	0.37	0.78	0.78	0.00	0.00	0.00	0.41	0.41	0.50	0.50	0.60	0.60	0.00	0.00	0.00
Ground surface temperature (°C)	Max	65.28	40.41	59.91	38.92	47.77	34.05	25.81	21.86	13.72	31.97	30.98	29.46	28.90	28.05	28.39	1.50	0.55	-0.33
	Min	29.15	29.06	26.54	26.31	28.28	28.76	-0.09	0.01	-0.60	29.12	28.73	25.33	25.33	27.10	27.65	-0.29	-0.47	-0.62
	Mean	48.06	35.24	38.08	32.17	32.41	30.01	12.82	5.90	2.39	30.00	29.64	27.66	27.66	27.45	27.94	0.36	-0.01	-0.49
Wet-bulb temperature (°C)	Max	29.90	29.90	29.80	29.50	28.00	27.80	1.30	1.10	0.30	27.80	27.90	27.00	26.90	26.70	26.60	0.40	1.70	0.30
	Min	26.30	26.20	25.90	25.40	25.30	25.40	-0.90	-0.80	-0.80	26.80	26.60	25.00	24.10	26.10	25.90	-0.10	0.10	0.00
	Mean	28.15	28.24	27.65	27.51	26.58	26.63	-0.09	0.14	-0.06	27.19	27.07	26.50	25.80	26.34	26.19	0.13	0.70	0.15
Globe temperature (°C)	Max	53.50	53.20	48.70	50.80	42.90	43.40	7.80	2.50	7.00	30.80	30.40	29.40	28.80	28.50	28.20	0.80	1.90	0.40
	Min	28.70	28.60	26.10	25.50	27.20	27.40	-4.70	-4.60	-2.00	29.10	28.50	25.10	24.20	27.20	27.10	0.30	0.00	0.00
	Mean	41.59	42.26	35.29	36.04	31.50	31.20	-0.67	-0.74	0.30	29.77	29.26	27.61	26.67	27.74	27.56	0.51	0.94	0.19
Shortwave radiation downward (W/m^2)	Max	972.41	997.55	998.92	1056.38	569.01	597.19	122.02	60.46	13.86	10.11	10.73	5.05	3.23	8.86	8.56	1.52	2.88	1.64
	Min	12.68	12.83	5.05	2.17	17.73	17.11	-157.70	-147.61	-51.51	2.57	1.05	1.24	1.05	1.24	1.05	-1.52	0.19	-0.93
	Mean	513.26	527.02	280.32	284.54	129.08	139.16	-13.77	-4.23	-10.07	3.12	3.36	2.76	2.00	2.96	2.57	-0.25	0.76	0.39
Shortwave radiation upward (W/m^2)	Max	49.71	191.97	54.62	212.89	32.62	106.41	-1.88	0.26	-4.21	6.51	9.53	4.91	4.73	3.26	5.73	-0.54	1.33	-1.34
	Min	5.71	7.60	3.26	3.80	2.46	6.66	-146.32	-163.18	-73.79	3.26	3.80	2.46	1.93	1.66	3.80	-3.01	-1.48	-3.27
	Mean	29.37	99.93	18.14	62.56	10.26	29.27	-70.56	-44.42	-19.01	4.19	5.69	3.08	3.51	2.56	4.15	-1.50	-0.42	-1.60
Longwave radiation downward (W/m^2)	Max	479.09	472.12	478.41	471.44	473.97	472.95	19.01	18.62	6.01	450.03	448.20	468.31	463.28	447.31	444.91	3.20	5.02	2.87
	Min	433.82	431.82	441.20	437.45	446.84	444.90	-8.09	-7.92	-5.86	438.64	436.28	438.28	436.19	434.39	432.32	0.55	0.42	1.00
	Mean	460.57	453.12	460.07	456.94	456.10	456.52	7.45	3.13	-0.42	443.37	441.54	453.01	450.53	440.81	438.63	1.83	2.49	2.19
Longwave radiation upward (W/m^2)	Max	743.79	548.13	697.67	537.76	601.39	504.98	202.26	165.91	96.41	491.41	485.11	475.45	471.98	466.67	468.75	9.54	3.47	-2.08
	Min	473.50	472.97	457.35	455.94	468.10	471.08	-0.54	0.04	-3.75	473.33	470.87	450.06	450.02	460.79	464.18	-1.83	-2.86	-3.84
	Mean	608.66	513.26	533.95	492.97	495.01	479.00	95.40	40.97	16.02	478.87	476.59	464.27	464.30	462.96	465.99	2.28	-0.03	-3.04

Appendix B. The pertinent data of COMFA energy budget

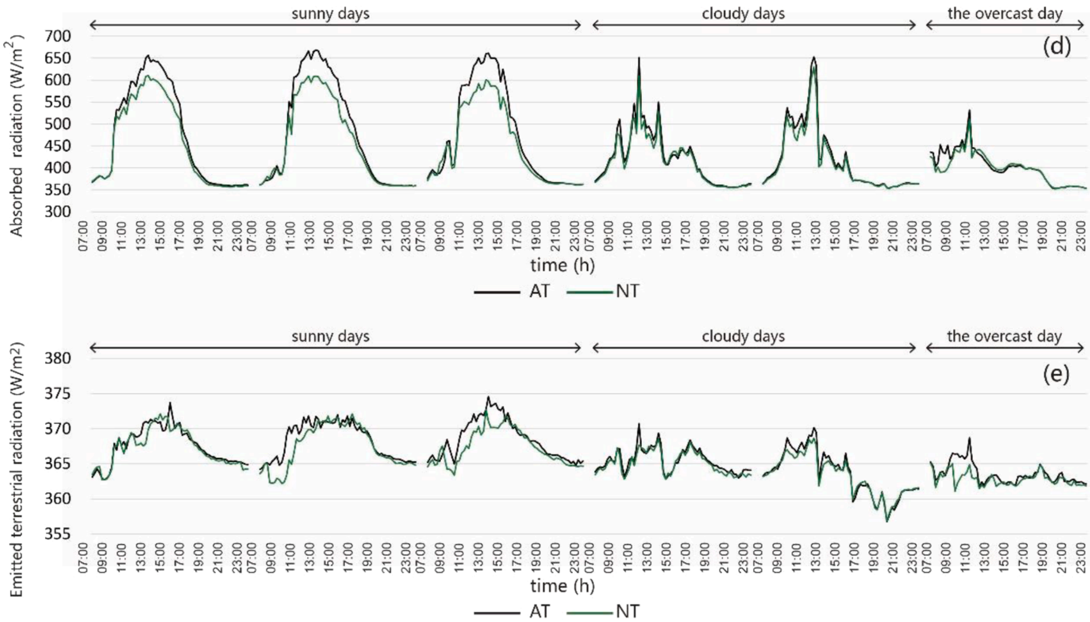
Weather condition	Time	Data type	Playing soccer games Children		Young athletes		Adults		Walking Children		Young athletes		Adults		Playing soccer games Children	Young athletes	Adults	Walking Children	Young athletes	Adults
			AT	NT	AT	NT	AT	NT	AT	NT	AT	NT	AT	NT	AT-NT					
Sunny days	Daytime	Max	613.19	562.29	574.32	515.91	480.75	422.12	398.69	348.55	347.74	289.66	303.96	244.03	59.78	72.03	71.55	59.87	70.59	71.71
		Min	314.92	311.72	339.41	336.33	247.46	244.36	103.85	100.51	117.43	114.17	73.17	71.78	-23.73	-34.88	-34.36	-22.58	-33.51	-32.70
		Mean	460.39	435.86	464.49	436.41	371.66	343.60	247.50	222.99	240.01	212.04	195.90	167.37	24.53	28.08	28.06	24.51	27.97	28.54
	Nighttime	Max	320.87	319.60	348.35	346.00	255.89	253.53	108.86	107.69	124.95	122.60	80.20	77.65	3.22	4.27	4.26	3.20	4.21	4.54
		Min	305.88	306.02	331.77	329.67	239.89	237.73	95.33	95.32	109.82	107.66	66.85	64.35	-1.69	-1.02	-0.95	-1.51	-0.86	-0.54
		Mean	313.29	312.90	337.05	335.70	244.96	243.61	101.95	101.58	114.61	113.31	71.14	69.46	0.38	1.35	1.35	0.38	1.30	1.68
Cloudy days	Daytime	Max	605.46	585.36	531.57	484.57	438.59	392.10	390.73	370.83	306.62	261.05	263.67	217.60	53.04	55.22	54.89	52.30	54.27	53.98
		Min	311.07	308.88	322.70	319.99	232.16	229.47	103.11	101.56	104.54	101.87	62.07	59.45	-19.74	-11.49	-11.04	-19.12	-10.37	-8.93
		Mean	393.61	385.36	401.86	391.87	309.60	299.61	181.85	173.57	179.05	169.08	134.87	124.63	8.25	9.99	9.99	8.28	9.97	10.25
	Nighttime	Max	321.94	321.91	337.75	337.23	246.08	245.38	111.81	111.30	116.65	115.70	72.37	71.32	1.73	3.44	3.32	1.70	3.07	3.57
		Min	303.01	302.87	312.71	312.55	222.72	222.46	96.76	96.27	96.00	95.58	54.80	53.77	-1.40	-2.57	-2.35	-0.92	-2.00	-1.86
		Mean	314.73	314.55	329.99	329.32	238.52	237.80	104.75	104.48	109.32	108.56	65.94	64.85	0.17	0.68	0.72	0.27	0.76	1.09
	Daytime	Max	480.75	461.40	468.31	436.95	375.35	344.87	267.80	250.38	243.54	214.61	198.43	170.39	60.36	50.31	50.49	60.77	50.73	51.94
		Min	318.29	319.35	337.70	337.76	246.22	246.31	108.43	109.54	116.90	117.05	74.59	74.43	-13.02	-12.21	-12.15	-12.88	-12.08	-11.41

(continued on next page)

(*continued*)

Weather condition	Time	Data type	Playing soccer games						Walking						Playing soccer games			Walking		
			Children		Young athletes		Adults		Children		Young athletes		Adults		Children	Young athletes	Adults	Children	Young athletes	Adults
			AT	NT	AT	NT	AT	NT	AT	NT	AT	NT	AT	NT	AT-NT					
The		Mean	367.55	364.04	385.87	380.46	294.20	288.89	157.42	154.10	164.58	159.47	121.56	116.12	3.51	5.40	5.31	3.32	5.11	5.44
overcast	Nighttime	Max	312.96	313.47	330.44	331.51	238.95	239.93	102.92	103.60	109.66	110.53	66.49	66.71	-0.35	0.94	0.86	-0.37	0.70	1.12
day		Min	302.15	303.70	321.79	321.48	230.40	230.13	92.45	93.98	101.19	101.12	57.70	57.73	-2.68	-2.14	-2.06	-2.63	-1.95	-1.59
		Mean	307.73	308.88	325.02	325.37	233.58	233.95	97.96	99.13	104.39	104.79	61.35	61.48	-1.15	-0.36	-0.37	-1.17	-0.41	-0.12

Appendix C. The energy budget value and each energy flux of children group playing soccer games: (a) Metabolic heat (b) Sensible convective heat exchange (c) Evaporative heat loss (d) Absorbed radiation (e) Emitted longwave radiation



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