Developing a thermal suitability index to assess artificial turf applications for various site-weather and user-activity scenarios

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HIGHLIGHTS

- We measured thermal condition of artificial & natural turfs in three weather types
- Artificial turf (AT) notably increases surface and air temperatures on sunny days
- Thermal sensation among users with various activities were compared based on mPET
- A 9-point thermal suitability index is developed to assess AT in design and use
- AT is an alternative to natural turf only for limited site and user scenarios

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ABSTRACT

Lawns are highly recognized and indispensable elements in the urban landscape. Due to water-saving, low maintenance cost, and avoided health-environmental impacts of agrochemical usage, artificial turf (AT) has increasingly replaced some natural turf (NT) sports fields and recreational lawns. It remains controversial whether AT is a healthy alternative to NT. We asked the research question, "Where and for whom the AT is (or isn't) suitable regarding user thermal sensation partaking various activities?" We established a field experiment at adjoining AT and NT fields in humid-tropical Hong Kong. Detailed microclimatic data were recorded under sunny, cloudy and overcast weather conditions to calculate the modified physiological equivalent temperature (mPET) as a thermal comfort index. Activities covering a range of metabolic rates were selected to evaluate user thermal sensation. AT experienced considerably raised ground surface temperatures on sunny days with a consequential increase in near-ground ambient air temperatures and the environs. The inter-turf temperature difference was somewhat subdued under cloudy and overcast weather. A regression model allowed the successful development of a nine-point thermal suitability index (TSI) to assess AT applications and provide a simple rule-of-thumb for design practice. To avoid undue heat stress, AT use can only be recommended for certain site-weather and user-activity scenarios. The TSI can be applied to other climatic zones by gleaning on-site microclimatic data and enlisting the proposed regression-modelling method. A comprehensive AT assessment scheme can be developed by incorporating the TSI to inform future AT installation and use decisions.

Keywords: Natural and artificial turf; Thermal comfort; Modified physiological equivalent temperature; User activity; Thermal suitability index; Turf design and application

1. Introduction

1.1. *Controversy about the application of artificial turf*

Due to savings in irrigation-water usage and maintenance cost, artificial turf has increasingly replaced natural turf in sports fields, and lawns in architectural, landscape, and urban design (Schneider et al., 2014). However, its adoption and conversion as a substitute for natural grass have remained controversial regarding impacts on the environment and human health (Cheng et al., 2014; Watterson, 2017). Some studies provided evidence of the litany of direct and indirect harmful effects of artificial turf. Others have focused on lower environmental impacts based on life-cycle assessment, mainly due to relatively low maintenance requirements.

1.1.1. *Concerns on negative environmental and health impacts*

Under the looming influence of climate change, climate-sensitive environmental planning and design measures that adopt the nature-based solution are preferred. They include but are not limited to: increasing urban greenery and vegetation to mitigate the urban heat island (UHI) effect (Farhadi et al., 2019) and reduce the carbon footprint (Strohbach et al., 2012); increasing pervious surfaces to decrease water runoff and improve groundwater recharge (Chithra et al., 2015). Creating and conserving natural grass sites such as lawns or turfs in cities can sustain their evaporative cooling properties to suppress temperature rise (Salata et al., 2015).

Artificial turf is usually made of surficial synthetic pile fibers that emulate natural grass leaf blades anchored in a granular infill substrate which could be rubber granules (Fleming, 2011). It is characterized by low albedo, water-holding capacity and specific heat to induce notable heat absorption and retention (Aoki, 2009; Yaghoobian et al., 2010). Such fundamental thermal properties can significantly increase ground surface temperatures and consequently increase ambient air temperatures near the ground as well as its surroundings (Jim, 2016). Many investigations have been conducted to enhance understanding of artificial turf impacts on surface and ambient temperatures (Jim, 2017; Petrass et al., 2014; Ramsey, 1982; Thoms et al., 2014). In some extreme cases, the surface temperature of artificial turf can be 30°C higher than natural grass (Loveday et al., 2019; McNitt and Petrunak, 2010). A study shows that using lighter and highly-reflective colors for either the turf infill or the fiber or both can only achieve limited surface temperature reduction (Penn State's Center for Sports Surface Research, 2012). For example, changing the fiber color from green to white achieves an approximately 6 °C reduction in artificial turf surface temperature. Such a reduction is limited when compared with the considerable thermal contrast between AT and NT, and it becomes insignificant after a couple of hours of radiative heating. Concerning climate mitigation, replacing natural ground with heat-absorbent artificial turf may be counter-productive.

The on-site and off-site chemical toxicity of artificial turf on the environment and human health has raised concerns (Li et al., 2010; Nilsson et al., 2008). The accumulation of waste materials on the synthetic leaf blades and substrate granules which have limited self-cleaning capability may foster the growth of harmful bacteria to aggravate infection of wounds, including the hazardous health risk of methicillin-resistant *Staphylococcus aureus* (MRSA) (Waninger et al., 2011).

1.1.2. Supportive views on applying artificial turf

Lawns denote a highly recognized and indispensable element in the urban landscape (Ignatieva et al., 2017; Robbins, 2012). However, to maintain the natural grass fields' thriving, green and aesthetic appeals to people, a substantial amount of irrigation is needed (Milesi et al., 2005). In some European, Australian, and American cities (particularly, cities in arid and semi-arid climatic regions), watering for grass fields is limited during hot summers (Hogue and Pincetl, 2015), which can cause decline and withering of the natural turf. Such periodic degradation demands additional restoration works (Ignatieva et al., 2020).

The application of toxic chemicals in lawn fertilization and pest and weed control has raised ecological and health concerns (Karr et al., 2007; Penick, 2013; Robbins et al., 2001). Under such circumstances, some quarters of the industry have advocated artificial turf as a "green and environment-friendly" product based on some commonly expressed justifications. They include requiring only occasional and a small amount of watering, and not requiring fertilizing, mowing, weeding and pest control. Some lifecycle assessments show the environmental benefits of using artificial turfs. Investigation on the use-times for both natural turf and artificial turf indicates a longer available time in a year-round period due to shorter maintenance time and stronger resistance to rainfall impacts on field playability (Simon, 2010). Recent studies on sports safety indicate no significant difference in injury occurrence between artificial and natural turfs (Calloway et al., 2019).

1.2. Research question

The application of artificial turf is not limited to outdoor sports fields. It has been adopted in various landscape and urban designs, including semi-indoor and indoor spaces. The fundamental difference between target functions and main design goals could largely explain the controversy mentioned above, as to whether artificial turf is a suitable choice depends largely on the functions and user groups. In other words, it is important to correctly understand how the advantages and disadvantages of natural turf and artificial turf affect the achievement of design goals before deciding on the choice. As discussed in the above background literature sections, many studies cover a broad range of topics about natural and artificial turfs and their advantages and disadvantages, but most studies tend to favor one against the other. In other words, most studies attempt to conclude to convince users that one is better than the other. Comparative research on applicability analysis is scarce.

Thermodynamic properties and thermal comfort are the most controversial topics about the two turf types. Regarding the thermal environment, similar to most ground-surface materials used in the built environment, the surface temperature of artificial turf largely depends on climatic factors, particularly incoming solar radiation and wind speed (Devitt et al., 2007). The incoming solar radiation is affected by cloudiness and sky conditions. The geometry of surrounding buildings affects shading and ventilation (wind speed). The body type, clothing, activities, and corresponding physiological indicators (such as metabolic rate) vary notably among user groups. Therefore, it is difficult to judge the suitability of artificial turf, as the influence of the above factors on the environment and health can vary considerably. Thus, determining the suitability of applying artificial turf demands location-specific assessments.

Considering the above issues, the basic premise of this study is to find the basis to install the artificial turfs where they are needed and suitable to most users and activities. In other words, we would avoid artificial turfs where users are more sensitive to their heat-related health impacts and have higher requirements on surface properties. This study aimed to provide quantitative information to answer the critical question: "Where and for whom the artificial turf is (or isn't) suitable regarding user thermal sensation partaking various activities?”.

2. Materials and methods

To answer the above research question, we designed a comparative experiment on the thermal environment of artificial turf (AT) and natural turf (NT) under three main weather types. Based on field measurements of the thermal conditions of AT and NT, we evaluated the suitability of AT and NT for various potential user groups by incorporating the user characteristics (activities and clothing when using the sites).

2.1. Synchronized co-located measurement of the thermal environment

This section introduces the study sites, weather conditions, design of the controlled experiment, and the microclimatic instruments. The thermal comfort condition is jointly regulated by air temperature, humidity, wind speed, and radiation. However, the major difference between AT and NT in regulating thermal comfort conditions lies in their differential modification of heat fluxes (Gustin et al., 2018). Therefore, all variables of background weather condition and ambient environment had to be controlled in this study. Accordingly, we implemented a temporal-synchronized co-located measurement campaign of AT and NT. The study site is the main sports center of the University of Hong Kong, situated at a large coastal open space on the southwest side of Hong Kong Island (Fig. 1). This study enlisted two adjacent sports fields with a very high site-averaged sky view factor (SVF > 0.9). Especially, the two instrument locations situated at the center of the sports fields are well exposed to sunlight and have a high permeability to air ventilation (SVF > 0.92 at the measurement point) with no nearby obstacles. Since the sports center, as a high-standard sports facility, hosts a large number and range of sports events and activities, the NT field is irrigated regularly, and the AT surface is properly maintained. The proximity of the two sites facilitated the design of a well-controlled experiment.

(Insert Fig. 1 here)

Fig. 1. Locations of the study sites and microclimatic monitoring instruments in humid-subtropical Hong Kong. The inset photographs show the artificial turf, natural turf, and instrument set.

The inset picture at the right side of Fig. 1 and

Table ***1*** shows the monitoring instruments. To ensure data integrity, continuity, and reliability, each measurement location was equipped with two replicated instruments sets (main and backup). Such a setup ensured that the experimental data would not be interrupted by random factors and instrument failures. The two duplicated datasets are very similar, with no statistically significant difference. Therefore, we used the data from the main set for further analysis. All sensors were calibrated and tested before the start of the measurement campaign.

Table 1

The detailed technical information of the instruments used in the microclimatic measurements at the study sites.

(Insert Table 1 here)

In temperate, subtropical, and tropical climate zones, summer is a period of high heat-related health risks (e.g., heat stroke). Therefore, the measurement campaigns were conducted in the summer (from July to August). The available measurement dates depended on the simultaneous availability of both sports fields for our research (outside use and maintenance periods) and weather conditions. The measurements were not conducted under extreme inclement weather conditions such as typhoons and rainstorms. In Hong Kong, the sky condition is complex (Ng et al., 2007). The cloud amount could change substantially and quickly in a single day to induce a complicated diurnal profile of global solar radiation. To understand the influence of weather on the thermal performance of AT and NT, we chose days with representative specific weather types. In sum, we collected data of six complete days representing three main weather types (cloudy, overcast, sunny) that complied with our selection criteria (

Table **2**).

Table 2
The weather conditions on the six measurement days: sunny, cloudy, and overcast, respectively. Both the data gleaned at the study sites and recorded by the government weather station (Hong Kong Observatory, HKO) are listed.
(Insert Table 2 here)
[a] Bright sunshine refers to solar radiation intensity I* ⩾ 120 W/m^2.

2.2. Evaluation of thermal comfort

2.2.1. Radiant heat from exposure to AT and NT environment

Mean Radiant Temperature (T_{mrt}) is a fundamental parameter to calculate the thermal comfort index. It evaluates the heat load on a person by assessing the radiant heat received by the human body (Fanger, 1970; Tredre, 1965). A commonly used T_{mrt} calculation method (Equation 1), based on the theory of Kuehn et al. (1970), employs the globe temperature T_g (˚C) measured by a standard globe thermometer (a black-painted copper sphere with a diameter of 150 mm and a thickness of 0.4 mm).

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.10 * 10^8 * v^{0.6}}{\varepsilon * d^{0.4}} \left(T_g - T_a\right) \right]^{0.25} - 273.15 \qquad (1)$$

where T_{mrt} is Mean Radiant Temperature; ε is the emissivity of the globe (0.95 for the standard black globe thermometer); d is the globe diameter in meter (0.15 for the standard black globe); T_a is measured air temperature (˚C); T_g is globe temperature measured by the globe (˚C); v is wind speed (m/s). However, previous studies pointed out the limitation of using standard black globes in outdoor environments (Thorsson et al., 2007) as it overestimates the influence of short-wave radiation (Olesen et al., 1989). In an environment with intense direct solar radiation, this limitation could introduce bias to the calculation since the NT surface has a higher albedo (which reflects more solar radiation). To overcome the above limitation, the method proposed by Matzarakis et al. (2010) was adopted to calculate T_{mrt}. The entire surroundings of a measurement location are assumed to consist of a total of n isothermal surfaces, and each isothermal surface has a corresponding spherical solid angle factor F_i. In our study, as mentioned in Section 2.1, the two adjacent sports fields are flat and have a very high sky view factor close to 1 with no obstacles near the measuring locations. Therefore, the entire surroundings of the measurement locations are assumed to be divided into two parts, which are sky and ground. Correspondingly, the F_i for both parts are estimated as 0.5. In the outdoor environment, there are two components of radiant heat from each isothermal surface i, which are long-wave radiation E_i and diffuse and reflected solar radiation D_i. In this study, E_i is directed measured by the Kipp and Zonen CNR4 Net radiometer (Section 2.1). As a special surface, the sky has an additional component - direct solar radiation, which is time and geolocation-dependent (dependent on the sun elevation angle γ, and the solar radiation intensity I^*). Together with the surface projection factor f_p which can be calculated from Equation 2 (Matzarakis et al., 2007). Based on the commonly used calculation method (Fanger, 1970; Jendritzky, 1990; Jendritzky and Nübler, 1981), T_{mrt} can be calculated using Equation 3.

$$f_p = 0.308 \times \cos\left[\frac{\gamma(0.998 - \gamma^2)}{5 \times 10^4}\right] \tag{2}$$

$$T_{mrt} = \left[\frac{1}{\sigma}\sum_{i=1}^{n}\left(E_i + \alpha_k \frac{D_i}{\varepsilon_p}\right)F_i + \frac{f_p \alpha_k I^*}{\varepsilon_p \sigma}\right]^{0.25} - 273.15 \tag{3}$$

where σ is the Stefan–Boltzmann constant ($5.67*10^{-8}$ W/(m^{2}K^4)); ε_p is the emission coefficient of the human body (standard value 0.97); α_k is the absorption coefficient of the irradiated body surface area of short-wave solar radiation (standard value 0.7). However, the CNR4 only measures global solar radiation. It does not separately measure direct solar radiation and diffuse/reflected solar radiation. In that case, the ratio of diffuse to global radiation is set based on a typical estimation by Brown and Gillespie (1995). Specifically, diffuse radiation can be estimated as 10% of the total amount under clear sky conditions.

2.2.2. Calculation of mPET thermal comfort index

In this study, the modified physiological equivalent temperature (mPET) (Chen and Matzarakis, 2018) was selected as the thermal comfort index to compare AT and NT. The mPET is a further development of the physiological equivalent temperature (PET), which is a well-known and widely used universal index for the biometeorological assessment of the thermal environment (Höppe, 1999; Mayer and Höppe, 1987). Both PET and mPET were developed based on the Munich Energy-Balance Model for Individuals (MEMI), a bio-climatological model of the human body's energy balance. According to the MEMI, mPET can be calculated based on the measured T_a (˚C), v (m/s), T_{mrt} (˚C), water vapor pressure (p_a, hPa), metabolic rate (M) and clothing index (clo). The value p_a was calculated from measured T_a and *RH* using Equation 4 (Cena and Clark, 1981):

$$p_a = RH * 10 * exp(16.6536 - \frac{4030.183}{T_a + 235}) \quad (4)$$

In subtropical Hong Kong, wind and humidity are influential factors of thermal comfort and thermal sensation (Ng and Cheng, 2012). Therefore, we enlisted mPET, which is superior for overcoming the limited sensitivity to wind speed and humidity in the original PET (Chen and Matzarakis, 2018). The T_a, v, T_{mrt}, p_a depend on actual measurements of the thermal environment, and the M and clo are user characteristics. Therefore, the suitability of applying artificial turfs is not only determined by the objective thermal environment but also by subjective factors about user activities (e.g., either relaxing or sports). In this study, combinations of M and clo were set to investigate the thermal comfort condition of different user groups. The energy released by metabolism is regulated by actual muscular activity (MacLaren and Morton, 2011). A series of M was used to represent activities that usually happen on lawns (Table 3). Either a summer dressing style or a professional athlete dress code (Li and Wang, 2018) with a usual value of M = 0.3 clo was used in our calculations.

Table 3
A list of user activities commonly conducted on lawns and their corresponding metabolic rate (The values are relevant to both common citizens and professional athletes).
(Insert Table 3 here)
Source: ISO (2005)

2.2.3. Thermal sensation and suitability of using artificial turf

The thermal sensation is subjective and closely related to the preferences of different groups of people. People living in different climatic zones with various cultural backgrounds have different levels of physiological and mental adaptation (Kántor et al., 2012). The actual impact of the same PET value on different groups of people tend to vary (Table 4). In the present study, we use the results from a previous questionnaire survey in Hong Kong as the criteria to evaluate thermal perception to match the local study area. It was conducted by Ng and Cheng (2012) to understand the thermal sensation of people in hot and humid climatic conditions. It employs a transverse thermal comfort survey as the experimental method, widely used and proved to be fit-for-purpose in outdoor thermal comfort research in various climatic zones. Specifically, field measurement was conducted to record the immediate micro-meteorological environment, and the subject's demographic information and thermal sensation were recorded simultaneously by a questionnaire. A total of 3639 diverse subjects were evaluated during an extended period spanning summer, autumn and winter across two years, providing a broad range of physical environmental condition and PET from as low as 12 ˚C to over 41 ˚C.

Table 4

PET-based thermal sensation vote and physiological heat or cold stress in different climate zones (Köppen climate classification). Our proposed 9-point thermal suitability index (TSI) scale has been added to the table.

(Insert Table 4 here)

[a] Based on the study of He et al. (2015).

[b] Based on the study of Ng and Cheng (2012), and used in this study.

[c] Based on the study of Matzarakis et al. (1999).

2.3. Developing a thermal suitability index (TSI)

We developed a thermal suitability index (TSI) to assess AT in architectural and urban designs based on potential users' thermal comfort and thermal perception. Multiple linear regression was computed to assess the relationship between the thermal suitability (response variable) and key controlling factors (predictor variables). We expect the TSI to be a simple and straightforward rule-of-thumb explained in layman language so that designers could easily understand and implement it in their practice. We hope to break the knowledge barrier to bridge science with policy and practice. Table 4 includes our proposed 9-point Likert TSI score ranging from -4 to 4 (based on a 9-point Likert scale). For example, a condition without thermal stress in the AT environment will be assigned a TSI score of 0. The medium heat stress in AT environment will correspond to a TSI score of 2 and a slightly cool condition -1. Our TSI score is designed as a continuous instead of a categorical variable so that a value with decimal can denote pro-rata and linearly a physically meaningful thermal condition.

Physically, the TSI score based on user thermal sensation is jointly regulated by key variables of air temperature, humidity, wind speed, radiation, human activities, and clothing. However, not all factors could be fully controlled by design measures. Many influential factors largely depend on the current site microclimate and background weather. For example, under subtropical weather and in the compact urban context of Hong Kong, the background humidity often remains at a relatively high level most of the time (Ng and Cheng, 2012), and wind speed depends on air ventilation of the site and environs (Ng, 2009). Typically, light summer clothing (briefs, long light-weight trousers, open-neck shirt with short sleeves, light socks and shoes) has a usual value of M ≤ 0.5 clo. However, during hot and humid summertime in tropical or sub-tropical areas like Hong Kong, the typical clothing (briefs, shorts, open-neck shirt with short sleeves, light sock and sandals) has an M value of 0.3 clo (Fanger, 1970). Therefore, the two essential but controllable factors of TSI are human activities and global solar radiation. Specifically, human activities depend on the design purpose of the site (whether the lawn surface is a sports field or a public open space for leisure). The global solar radiation is determined by site location (outdoor locations with high solar accessibility, or outdoor or semi-outdoor locations mostly under shading, or indoor space without global solar radiation) and weather condition (clear sky, partially cloudy, or overcast, which change with the site operating hours). Therefore, we included user activity, weather type and global solar radiation as predictor variables, the first two of which are categorical variables. Dummy variables were introduced to express the categorical predictor data. The model equation is shown in Equation 5:

$$\begin{aligned} \mathit{Suitability\ score} &= \beta_0 + \beta_1 I(\mathit{user\ activity}\ 0.8\ \mathit{Met}) \\ &+ \beta_2 I(\mathit{user\ activity}\ 1.0\ \mathit{Met}) + \beta_3 I(\mathit{user\ activity}\ 1.2\ \mathit{Met}) \\ &+ \beta_4 I(\mathit{user\ activity}\ 1.6\ \mathit{Met}) + \beta_5 I(\mathit{user\ activity}\ 2.0\ \mathit{Met}) \\ &+ \beta_6 I(\mathit{user\ activity}\ 4.7\ \mathit{Met}) + \beta_7 I(\mathit{weather\ type\ cloudy}) \\ &+ \beta_8 I(\mathit{weather\ type\ overcast}) + \beta_9 (\mathit{solar\ radiation})^* \end{aligned} \tag{5}$$

where *I(user activity ..Met)* is a dummy variable representing user activities at various metabolic rates (reference = user activity - Sports - running at 15 km/h, see Table 3). *I (weather* *type ..)* is a dummy variable representing a specific weather type (reference = weather type sunny). β_0 is the model intercept. $\beta_1, \beta_2, \ldots, \beta_9$ are the slope of predictor variables. To evaluate the model performance, adjusted R^2 was adopted to provide a more precise indicator of the model correlation. It considers the total amount of predictor variables as an influential factor of model performance and avoids possible interference caused by the excessive number of predictors relative to the data. However, such interference did not concern the present study as the data amount is much larger than the number of predictor variables. Statistically, collinearity between predictors causes model overfitting. The variance inflation factor (VIF) was calculated for all predictor variables to suppress multicollinearity in the model. Moreover, a 10-fold cross validation was also performed to examine the robustness of the resultant model.

3. Results

3.1. Difference in air temperature, surface temperature and mean radiant temperature

Considering that most lawn use occurs during the daytime, we first extracted the data measured during the daytime for research (0600 to 1900 h, based on the local summer sunrise and sunset time). The surface temperature of the two turf types (AT and NT), as well as the air temperature and mean radiation temperature at 1.5 m height, were compared under three weather types, respectively ((Insert Fig. 2 here)

Fig. 2 left graph). Before performing the temperature comparison, wind speed measurements above the two turf types were examined to avoid the bias caused by the difference in wind condition. The average wind speed to two decimal places at both turfs was 0.42 m/s. The Analysis of Variance (ANOVA) and the Student's t-test also indicated no significant difference between the two groups of wind speed data.

The ANOVA test and the Student's t-test were performed to compare the average temperature values. The test results indicated a significant difference in surface and air temperatures between AT and NT and among three weather types, both at a significance level of $p < 0.05$. Especially, the surface temperature of AT was significantly higher than NT in all-weather types. The inter-turf difference in surface temperature was the largest in sunny weather, which reached 18.3 °C. In cloudy and overcast weather, the difference was 9.5 °C and 4.6 °C, respectively. The surface temperature of AT shot to a maximum of 74.6 °C on sunny days. Even on cloudy days with less solar radiation, it still attained 52.5 °C. The T_{mrt} followed a similar pattern: The averaged T_{mrt} of AT was 3.4 °C and 0.8 °C higher than NT in sunny and cloudy weather, respectively. Moreover, the terrestrial radiation from AT lifted the ambient air temperature over the turf surface by more than 0.5 °C in comparison with NT. However, the 0.4 °C inter-turf difference in T_{mrt} in overcast weather was statistically not significant.

The nighttime thermal environment is important for Hong Kong as hot nights could pose greater health threats to the public than hot days (Shi et al., 2019). The lawn is an essential element of urban green space, especially for compact urban areas lacking outdoor open space. We found that AT remained slightly hotter than NT in sunny and cloudy weather in the nighttime ((Insert Fig. 2 here)

Fig. 2 right graph). In overcast weather, AT and NT were similar in air temperature and T_{mrt}. This pattern indicated the subdued daytime insolation could influence nighttime AT performance.

(Insert Fig. 2 here)
Fig. 2. Comparison of daytime (left) and nighttime (right) surface temperature of AT and NT, as well as comparison of their corresponding air temperature and mean radiation temperature at 1.5 m height, under three weather types (quantile box-plot and mean value are shown).

3.2. Physiological heat stress of AT and NT and user thermal perception

In this section, physiological heat stress and users' thermal perception were compared between AT and NT in two ways, namely weather type and user activity. The results by weather types are shown in Fig. 3 left graph. We aggregated all types of activities and divided the data into three weather types.

The comparison showed no significant difference between AT and NT in the user physiological heat stress on cloudy and overcast days. The difference between the very hot situation and the hot situation was 3.2 % in cloudy weather. Notably, under the overcast weather with almost no direct solar radiation, the difference in user thermal sensation was slight between AT and NT. However, under sunny weather with strong solar radiation intensity, the proportion of hot and very hot situations in AT was 7.7% and 15.1% higher than NT, respectively.

The comparison results by user activities are shown in Fig. 3 right graph. NT provided a better thermal environment than AT for activities with a relatively low metabolic rate. The percentage of extreme heat stress in AT was 4.4%, 8.5%, and 13.5% for reclining, seated relaxed and standing relaxed, respectively. NT under the weather brought no extreme heat stress and less strong heat stress to users, thus creating a more satisfying or less stressful thermal environment for leisure. As expected, NT even occasionally brought a slightly cool sensation for users in relaxing, which is much needed to mitigate urban heat. Therefore, NT is more suitable for place-making for public open space.

(Insert Fig. 3 here)

Fig. 3. Comparison of physiological heat stress and users' thermal perception between AT and NT. The proportion of different physiological stress conditions has been plotted by weather type (left) and user activity (right).

Although NT performs better than AT for standing heavy activities and sports, both turfs could not provide thermal relief to users (especially the athletes) due to the inherently high metabolic rate of the activities and the hot summer in the subtropical climatic zone. Additional heatstroke prevention and cooling measures are necessary for athletes and heavy-activity users, even in NT fields. Therefore, we excluded the thermal index data of these two high metabolic-rate activities from our subsequent analysis of the temporal trend of heat stress of AT and NT to render the results more generalizable for the general public. The histograms in Fig. 4 shows the temporal distribution of various heat stress levels in AT and NT environments. It displays two noticeable differences: (1) Compared to AT, NT greatly reduced the extreme heat stress in 1200 to 1500 h; and (2) NT occasionally provided a slightly cool condition in the hour before sunset, bringing physical and mental comfort to citizens in hot weather.

(Insert Fig. 4 here)

Fig. 4. Daytime temporal trend of mPET of the two turf types in three different weather types. Slightly cool condition appears in NT before sunset.

3.3. Regression model and proposed thermal suitability index (TSI)

Following the method described in Section 2.3, we performed regression modelling to assess the relationship between thermal comfort-based suitability score and factors representing user activity, weather type, and incoming solar radiation. The resulting regression model is summarized in Table 5. It demonstrated a practically usable performance with an adjusted R^2 of 0.849 and an RMSE of 0.52. A 10-fold cross validation R^2 of 0.848 indicates the robustness of the resultant model. Except for the predictor variable Weather Type [Overcast], other predictor variables registered a significance level of $p < .0001$. The model itself had a significance level of $p < .0001$. The model performance values indicated the ready applicability of TSI as a practical rule-of-thumb for quick evaluation of AT suitability.

The VIF was calculated for all predictor variables, with a VIF < 2, indicating the absence of severe multicollinearity in the model. It was reasonable to find no collinearity between weather type and solar radiation in the model. Under different weather types, when the solar radiation was the same, the corresponding thermal comfort conditions might still be different. In cloudy weather, the AT surface would be randomly and alternately exposed to direct sunlight or shaded by clouds. For a specific period with a certain amount of incoming solar radiation, the measured AT surface temperature depended on the antecedent exposure or shading conditions in the previous several minutes due to the lag effect of surface temperature change. Sunny weather at user activity of 9.5 Met was not included in the model structure due to variable redundancy. Moreover, this particular permutation represented the strongest heat stress. As mentioned in Section 3.2, under such circumstances, both AT and NT were not able to provide thermal relief to users (particularly the athletes), and additional heatstroke prevention and cooling measures would be necessary. Even NT would demand measures to minimize heat-related health risks.

The regression model (Table 5) provides a simple equation to estimate the thermal comfort-based TSI score. The dummy variables took the value 1 or 0 to represent the presence or absence of the categorical feature. For example, to model a user activity of reclining (0.8 Met), we set the predictor variable user activity [0.8 Met] to 1 and set other variables of user activity to 0. This rule applied to all variables except the incoming solar radiation, which directly used the measured or estimated continuous data. We used a case scenario to apply the equation under overcast weather with total incoming solar radiation intensity of 150 W/m^2 and user activity of seated relaxed (1.0 Met). The equation would yield a TSI score of 1.2, corresponding to a slightly warm situation listed in Table 4.

Table 5
The resultant regression model shows the relationship between thermal comfort-based suitability score and factors representing user activity, weather type, and incoming solar radiation.

(Insert Table 5 here)

[a] Refer to Table 3 for the specific user activities with different levels of metabolic equivalent.

4. Discussion

4.1. AT is a possible alternative to NT but only for limited scenarios

It is true that AT demands less watering, fertilizing and other maintenance inputs than NT. However, in the cardinal interest of user thermal health and safety, it should be noted that AT is an acceptable alternative to NT but only for certain scenarios. This study found no significant difference between AT and NT in user thermal sensation in overcast weather when the direct solar radiation is absent and the incoming solar radiation is not strong. This finding indicates that it is acceptable to use AT to replace NT in locations and contexts with little direct solar radiation and only a limited amount of incoming solar radiation. In design practice, these contexts could be a semi-outdoor space or an outdoor space amply shaded by surrounding buildings most of the time. Before deciding whether AT should be installed, running a numerical simulation of solar accessibility of the project site would be wise to provide quantitative evidence on the shading regime, especially in summer.

For spaces well exposed to intense solar radiation, AT is not recommended due to users' high heat stress risk. AT increases the ambient air temperature by more than 0.5 °C. In extremely hot weather, even a small increment in air temperature could significantly drive the probability of heat-related health risks (Grundstein et al., 2018). Using AT cannot be recommended for the scenarios of users exposed to direct sunlight and engaged in heavy activities with a high metabolic rate. However, for indoor fields in stadiums and sports centers with proper building air ventilation, AT presents an acceptable substitute for NT, partly because it does not need an energy-intensive artificial daylighting system required by outdoor NT (Navvab, 1999).

Under intense solar exposure, the excessively heated AT surface could be cooled down by additional watering (Kanaan et al., 2020). However, as the cooling effect of watering on AT temperature is short-lived if not ephemeral (Jim, 2016; Serensits et al., 2011), frequent irrigation requiring a notable amount of water could discount the water-saving benefits of AT. In any case, spraying water during a game is impractical, hence this method of cooling AT fields could only have limited applicability.

4.2. Transferability of TSI to other climatic zones

Weather background (especially the incoming solar radiation regime) and the city context vary from location to location. As mentioned in Section 2.2.3, the thermal sensation varies among regions in different parts of the world. Moreover, the diverse cultural background also regulates dressing habits. Therefore, appropriate modifications would be needed before transferring and applying the present study results to other climatic zones. As our research methodology and workflow are straightforward, adjusting the TSI to match local natural and cultural conditions would be simple. Specifically, a controlled experiment similar to our field measurement campaign would be necessary for the cities where the suitability of using AT in design practice must be evaluated. Based on the empirical microclimatic data, the regression modelling method explained in Section 2.3 can be performed to establish the statistical relationship between the TSI score and key factors of the study site.

4.3. Imperative of holistic suitability evaluation of artificial turf

Our TSI to assess AT has been developed principally from the perspective of human thermal sensation, given the high priority to prevent heat-related health risks and ensure users' health. Some studies on the life-cycle analysis of artificial turfs have indicated a high environmental cost due to the cradle-to-grave ecological footprints of raw material extraction, product manufacturing, air and water pollution, as well as health burden during usage, and waste disposal concerning the limited useful life span.

With a limited understanding of AT's total environmental and health encumbrance, developing a holistic suitability evaluation scheme is pertinent. It can be conceived for effective knowledge transfer from science to practice that is readily applicable to the industry and easily understood by policy-makers and laypersons. The example of the Solar Photovoltaic System (solar PV panels) can offer enlightenment. Similar debates and controversies on solar PV panels have gone on for many years. Efforts have been made in developing guidance notes and assessment criteria in many countries, which provide evidence-based decision-making on their installation. In a similar vein, AT should only be used under suitable scenarios. The simple and straightforward TSI developed in this study can be incorporated into a comprehensive suitability evaluation scheme for the science-informed application of artificial turf in urban open space and architectural design.

4.4. Limitations and future works

The measurements and experiments of the current research were carried out in the subtropical climate. Therefore, our study mainly observed the heat stress brought by AT in the hot summer climate. Consequently, it is a limitation that the present study cannot provide evidence for design practice in avoiding cold physiological stress. Future works could expand the measurements to other climatic regions and seasons. Currently, the investigation of thermal comfort is entirely based on in-situ measurements and calculations of the thermal comfort index.

No questionnaire surveys have been conducted to investigate the actual attitudes, behaviors, perceptions and health impacts in using both AT and NT sites. Questionnaires surveys of selected respondent groups regarding age, gender, body configuration, health status and sports training could be adopted in future research. Such surveys could be conducted together with a separate field experiment at another pair of AT and NT sites, which will also provide data for further external validation and fine-tuning of the model of suitability score. In addition, this study predicts thermal sensation based on typical contemporary clothing settings by assuming the clothing index as a single standard value. In future works, it would be valuable to include studies on traditional vernacular costumes from different cultural backgrounds to contribute to the design practice for equity and inclusion.

5. Conclusion

In this study, the thermal environments of artificial and natural turfs were measured and compared in different weather. It is found that the artificial turf significantly increased temperature but only on sunny days. Under the cloudy and overcast conditions, the difference between AT and NT was limited. Based on the data from a simultaneous and co-located measurement of the thermal environment in a site with adjoining artificial and natural turfs, thermal sensations among users conducting various activities were compared by calculating the mPET thermal comfort index. With these empirical measurement data and thermal comfort computations, we developed by regression modelling a new thermal suitability index to assess AT, aiming at informing the practical design and usage application. The index can contribute a necessary and critical part of a holistic suitability evaluation scheme to rationalize the application of artificial turf in urban open space and architectural design.

Last but not least, our finding can lead to the practical recommendation that artificial turf is a possible alternative to natural turf only for limited site-weather and user-activity scenarios. For many circumstances with harmful impacts on user health, the use of AT should be avoided. Thus, the application of AT in design practice should be evaluated by a case-by-case analysis. Urban planners, architects, landscape designers, policy-makers, and stakeholders need to understand that AT has been invented only to solve specific problems and cater to certain scenarios. It should not be regarded as a complete substitute for NT. It is also obviously biased to advocate the artificial turf is a “green and environment-friendly” product. AT is not a counterpart of NT. It is synthetic, not living grass. They are essentially two different entities conceived for different purposes that happen to have some overlapping functionality.

References

Aoki, T., 2009, Effect of solar illuminance and albedo on surface temperature of outdoor sport surfaces, *Nature and its Environment* **11:**40-48.

Brown, R. D., Gillespie, T. J., 1995, Microclimatic landscape design: creating thermal comfort and energy efficiency, Wiley New York.

Calloway, S. P., Hardin, D. M., Crawford, M. D., Hardin, J. M., Lemak, L. J., Giza, E., Forsythe, B., Lu, Y., Patel, B. H., Osbahr, D. C., Gerhardt, M. B., Mandelbaum, B. R., Baldwin, W. W., 2019, Injury Surveillance in Major League Soccer: A 4-Year Comparison of Injury on Natural Grass Versus Artificial Turf Field, *The American Journal of Sports Medicine* **47**(10)**:**2279-2286.

Cena, K., Clark, J. A., 1981, Bioengineering, Thermal Physiology and Comfort, Elsevier Science.

Chen, Y.-C., Matzarakis, A., 2018, Modified physiologically equivalent temperature—basics and applications for western European climate, *Theoretical and Applied Climatology* **132**(3)**:**1275-1289.

Cheng, H., Hu, Y., Reinhard, M., 2014, Environmental and health impacts of artificial turf: a review, *Environmental Science & Technology* **48**(4)**:**2114-2129.

Chithra, S., Nair, M. H., Amarnath, A., Anjana, N., 2015, Impacts of impervious surfaces on the environment, *International Journal of Engineering Science Invention* **4**(5)**:**27-31.

Devitt, D., Young, M., Baghzouz, M., Bird, B., 2007, Surface temperature, heat loading and spectral reflectance of artificial turfgrass, *Journal of Turfgrass and Sports Surface Science* **83:**68-82.

Fanger, P. O., 1970, Thermal comfort: Analysis and applications in environmental engineering, McGraw-Hill, New York.

Farhadi, H., Faizi, M., Sanaieian, H., 2019, Mitigating the urban heat island in a residential area in Tehran: Investigating the role of vegetation, materials, and orientation of buildings, *Sustainable Cities and Society* **46:**101448.

Fleming, P., 2011, Artificial turf systems for sport surfaces: current knowledge and research needs, *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology* **225**(2)**:**43-63.

Grundstein, A. J., Hosokawa, Y., Casa, D. J., 2018, Fatal Exertional Heat Stroke and American Football Players: The Need for Regional Heat-Safety Guidelines, *Journal of Athletic Training* **53**(1)**:**43-50.

Gustin, M., Fleming, P. R., Allinson, D., Watson, S., 2018, Modelling Surface Temperatures on 3G Artificial Turf, *Proceedings* **2**(6)**:**279.

He, X., Miao, S., Shen, S., Li, J., Zhang, B., Zhang, Z., Chen, X., 2015, Influence of sky view factor on outdoor thermal environment and physiological equivalent temperature, *International Journal of Biometeorology* **59**(3)**:**285-297.

Hogue, T. S., Pincetl, S., 2015, Are you watering your lawn?, *Science* **348**(6241)**:**1319-1320.

Höppe, P., 1999, The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment, *International Journal of Biometeorology* **43**(2)**:**71-75.

Ignatieva, M., Eriksson, F., Eriksson, T., Berg, P., Hedblom, M., 2017, The lawn as a social and cultural phenomenon in Sweden, *Urban Forestry & Urban Greening* **21:**213-223.

Ignatieva, M., Haase, D., Dushkova, D., Haase, A., 2020, Lawns in Cities: From a Globalised Urban Green Space Phenomenon to Sustainable Nature-Based Solutions, *Land* **9**(3)**:**73.

ISO, E., 2005, 7730. 2005. Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, *International Standardisation Organisation, Geneva* **147**.

Jendritzky, G., 1990, Methodik zur Räumlichen Bewertung der Thermischen Komponente im Bioklima des Menschen: Fortgeschriebenes Klima-Michel-Modell, na.

Jendritzky, G., Nübler, W., 1981, A model analysing the urban thermal environment in physiologically significant terms, *Archives for Meteorology, Geophysics, and Bioclimatology, Series B* **29**(4)**:**313-326.

Jim, C. Y., 2016, Solar–terrestrial radiant-energy regimes and temperature anomalies of natural and artificial turfs, *Applied Energy* **173:**520-534.

Jim, C. Y., 2017, Intense summer heat fluxes in artificial turf harm people and environment, *Landscape and Urban Planning* **157:**561-576.

Kanaan, A., Sevostianova, E., Leinauer, B., Sevostianov, I., 2020, Water Requirements for Cooling Artificial Turf, *Journal of Irrigation and Drainage Engineering* **146**(10)**:**05020004.

Kántor, N., Unger, J., Gulyás, Á., 2012, Subjective estimations of thermal environment in recreational urban spaces—Part 2: international comparison, *International Journal of Biometeorology* **56**(6)**:**1089-1101.

Karr, C. J., Solomon, G. M., Brock-Utne, A. C., 2007, Health Effects of Common Home, Lawn, and Garden Pesticides, *Pediatric Clinics of North America* **54**(1)**:**63-80.

Kuehn, L., Stubbs, R., Weaver, R., 1970, Theory of the globe thermometer, *Journal of Applied Physiology* **29**(5)**:**750-757.

Li, X., Berger, W., Musante, C., Mattina, M. I., 2010, Characterization of substances released from crumb rubber material used on artificial turf fields, *Chemosphere* **80**(3)**:**279-285.

Li, Z., Wang, Y., 2018, Study on the effect of professional sports clothing on sports physiology.

Loveday, J., Loveday, G., Byrne, J. J., Ong, B.-l., Morrison, G. M., 2019, Seasonal and Diurnal Surface Temperatures of Urban Landscape Elements, *Sustainability* **11**(19)**:**5280.

MacLaren, D., Morton, J., 2011, Biochemistry for sport and exercise metabolism, John Wiley & Sons.

Matzarakis, A., Mayer, H., Iziomon, M. G., 1999, Applications of a universal thermal index: physiological equivalent temperature, *International Journal of Biometeorology* **43**(2)**:**76-84.

Matzarakis, A., Rutz, F., Mayer, H., 2007, Modelling radiation fluxes in simple and complex environments—application of the RayMan model, *International Journal of Biometeorology* **51**(4)**:**323-334.

Matzarakis, A., Rutz, F., Mayer, H., 2010, Modelling radiation fluxes in simple and complex environments: basics of the RayMan model, *International Journal of Biometeorology* **54**(2)**:**131-139.

Mayer, H., Höppe, P., 1987, Thermal comfort of man in different urban environments, *Theoretical and Applied Climatology* **38**(1)**:**43-49.

McNitt, A. S., Petrunak, D., 2010, Evaluation of playing surface characteristics of various infilled systems, *University Park, PA: Center for Sports Surface Research, Pennsylvania State University*.

Milesi, C., Running, S. W., Elvidge, C. D., Dietz, J. B., Tuttle, B. T., Nemani, R. R., 2005, Mapping and Modeling the Biogeochemical Cycling of Turf Grasses in the United States, *Environmental Management* **36**(3)**:**426-438.

Navvab, M., 1999, Integration of Daylighting and Sport Lighting Systems Design for Turf Growth in an Indoor Football Stadium, *Journal of the Illuminating Engineering Society* **28**(2)**:**63-80.

Ng, E., 2009, Policies and technical guidelines for urban planning of high-density cities–air ventilation assessment (AVA) of Hong Kong, *Building and Environment* **44**(7)**:**1478-1488.

Ng, E., Cheng, V., 2012, Urban human thermal comfort in hot and humid Hong Kong, *Energy and Buildings* **55**(0)**:**51-65.

Ng, E., Cheng, V., Gadi, A., Mu, J., Lee, M., Gadi, A., 2007, Defining standard skies for Hong Kong, *Building and Environment* **42**(2)**:**866-876.

Nilsson, N. H., Malmgren-Hansen, B., Thomsen, U. S., Institut, T., 2008, Mapping, emissions and environmental and health assessment of chemical substances in artificial turf, Danish Environmental Protection Agency Copenhagen, Denmark.

Olesen, B., Rosendahl, J., Kalisperis, L., Summers, L., Steinman, M., 1989, Methods for measuring and evaluating the thermal radiation in a room, *ASHRAE transactions* **95:**1028-1044.

Penick, P., 2013, Lawn Gone!: Low-Maintenance, Sustainable, Attractive Alternatives for Your Yard, Potter/Ten Speed/Harmony/Rodale.

Penn State's Center for Sports Surface Research, 2012, Surface Temperature of Synthetic Turf, Penn State's Center for Sports Surface Research.

Petrass, L. A., Twomey, D. M., Harvey, J. T., 2014, Understanding how the Components of a Synthetic Turf System Contribute to Increased Surface Temperature, *Procedia Engineering* **72:**943-948.

Ramsey, J. D., 1982, Environmental heat from synthetic and natural turf, *Research Quarterly for Exercise and Sport* **53**(1)**:**82-85.

Robbins, P., 2012, Lawn people: How grasses, weeds, and chemicals make us who we are, Temple University Press.

Robbins, P., Polderman, A., Birkenholtz, T., 2001, Lawns and Toxins: An Ecology of the City, *Cities* **18**(6)**:**369-380.

Salata, F., Golasi, I., de Lieto Vollaro, A., de Lieto Vollaro, R., 2015, How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study, *Energy and Buildings* **99:**32-49.

Schneider, D., Hypes, J. A., Hypes, M. G., 2014, Synthetic Turf vs. Natural Grass, *Journal of Facility Planning, Design, and Management* **2**(2).

Serensits, T. J., McNitt, A. S., Petrunak, D. M., 2011, Human health issues on synthetic turf in the USA, *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology* **225**(3)**:**139-146.

Shi, Y., Ren, C., Cai, M., Lau, K. K.-L., Lee, T.-C., Wong, W.-K., 2019, Assessing spatial variability of extreme hot weather conditions in Hong Kong: A land use regression approach, *Environmental Research* **171:**403-415.

Simon, R., 2010, Review of the impacts of crumb rubber in artificial turf applications.

Strohbach, M. W., Arnold, E., Haase, D., 2012, The carbon footprint of urban green space—A life cycle approach, *Landscape and Urban Planning* **104**(2)**:**220-229.

Thoms, A. W., Brosnan, J. T., Zidek, J. M., Sorochan, J. C., 2014, Models for Predicting Surface Temperatures on Synthetic Turf Playing Surfaces, *Procedia Engineering* **72:**895-900.

Thorsson, S., Lindberg, F., Eliasson, I., Holmer, B., 2007, Different methods for estimating the mean radiant temperature in an outdoor urban setting, *International Journal of Climatology* **27**(14)**:**1983-1993.

Tredre, B. E., 1965, ASSESSMENT OF MEAN RADIANT TEMPERATURE IN INDOOR ENVIRONMENTS, *British Journal of Industrial Medicine* **22**(1)**:**58-66.

Waninger, K. N., Rooney, T. P., Miller, J. E., Berberian, J., Fujimoto, A., Buttaro, B. A., 2011, Community-associated methicillin-resistant Staphylococcus aureus survival on artificial turf substrates, *Medicine and Science in Sports and Exercise* **43**(5)**:**779-784.

Watterson, A., 2017, Artificial Turf: Contested Terrains for Precautionary Public Health with Particular Reference to Europe?, *International Journal of Environmental Research and Public Health* **14**(9)**:**1050.

Yaghoobian, N., Kleissl, J., Krayenhoff, E. S., 2010, Modeling the thermal effects of artificial turf on the urban environment, *Journal of Applied Meteorology and Climatology* **49**(3)**:**332-345.

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Table 1

The detailed technical information of the instruments used in the microclimatic measurements at the study sites.

Parameter	Abbreviation and unit	Sensor information	Sensor accuracy
Air temperature (at 1.5 m height)	T_a (˚C)	Hobo S-THB Thermistor, Bourne, MA, USA	± 0.2˚C
Turf surface temperature	T_s (˚C)	Apogee SI-111 Infrared radiometer, Logan, UT, USA	± 0.2˚C
Relative humidity (at 1.5 m height)	*RH (%)*	Hobo S-THB Thermistor, Bourne, MA, USA	± 2.5%
Wind speed (at 2.0 m height)	v (m/s)	Hobo S-WCA, Cup anemometer, Bourne, MA, USA	± 0.5 m/s
Global solar radiation	I^* and D_{sky}	Kipp & Zonen CNR4 Net radiometer, Delft, the Netherlands (sensors facing upwards)	< 5% W/m^2
Sky thermal radiation	E_{sky}		
Reflected solar radiation	D_{ground}	Kipp & Zonen CNR4 Net radiometer, Delft, the Netherlands (sensors facing downwards)	
Ground thermal radiation	E_{ground}		

Table 2

The weather conditions on the six measurement days: sunny, cloudy, and overcast, respectively. Both the data gleaned at the study sites and recorded by the government weather station (Hong Kong Observatory, HKO) are listed.

Date (yyyymmdd)	Weather type	Location	Aggregated incident solar radiation (MW/m^2)	Bright sunshine duration (h)[a]	Air temperature (T_a, ˚C)			Relative humidity (RH, %)
					Max	Min	Range	Mean (Min-Max)
20140705	Sunny	Site	24.49	9.8	34.4	28.3	6.1	80 (69-91)
		HKO	23.97	9.9	33.8	28.9	4.9	76 (65-84)
20140706	Sunny	Site	22.10	10.0	34.8	28.9	5.9	80 (67-88)
		HKO	20.60	7.5	32.9	27.9	5.0	79 (63-92)
20140707	Overcast	Site	6.48	4.5	30.5	27.7	2.8	87 (78-92)
		HKO	6.84	0.9	30.3	26.9	3.4	84 (77-91)
20140804	Sunny	Site	23.70	9.0	34.4	28.6	5.8	80 (67-92)
		HKO	20.91	6.9	32.7	27.2	5.5	81 (66-97)
20140805	Cloudy	Site	13.24	9.8	32.3	28.2	4.1	83 (73-88)
		HKO	10.69	2.0	30.7	27.3	3.4	86 (78-96)
20140812	Cloudy	Site	13.43	7.3	32.3	26.0	6.3	89 (82-99)
		HKO	13.84	3.4	31.4	25.3	6.1	85 (73-98)

[a] Bright sunshine refers to solar radiation intensity $I^* \geq 120$ W/m^2.

Table 3

A list of user activities commonly conducted on lawns and their corresponding metabolic rate (The values are relevant to both common citizens and professional athletes).

User activity	Metabolic rate (W/m^2)	Metabolic equivalent (MET)
Reclining	46	0.8
Seated relaxed	58	1.0
Standing relaxed (e.g., entertainment)	70	1.2
Standing, light activity (e.g., coaching)	93	1.6
Standing, medium activity (e.g., warming up)	116	2.0
Standing, heavy activity (e.g., training)	275	4.7
Sports - running at 15 km/h	550	9.5

Source: ISO (2005)

Table 4

PET-based thermal sensation vote and physiological heat or cold stress in different climate zones (Köppen climate classification). Our proposed 9-point thermal suitability index (TSI) scale has been added to the table.

Thermal perception	Physiological heat stress or cold stress	Proposed thermal suitability index (TSI) scale	PET for Beijing - warm temperate zone (°C) [a]	PET for Hong Kong - subtropical climate zone (°C) [b]	PET for Western/middle Europe - oceanic climate zones and the hybrid oceanic/continental climate zone (°C) [c]
Very cold	Extreme cold stress	-4	< −4	< 13	< 4
Cold	Strong cold stress	-3	−4~8	13–17	4~8
Cool	Medium cold stress	-2	8~16	17–21	8~13
Slightly cool	Slight cold stress	-1	16~22	21–25	13~18
Neutral	No thermal stress	0	22~28	25–29	18~23
Slightly warm	Slight heat stress	1	28~32	29–33	23~29
Warm	Medium heat stress	2	32~38	33–37	29~35
Hot	Strong heat stress	3	38~44	37–41	35~41
Very hot	Extreme heat stress	4	> 44	> 41	> 41

[a] Based on the study of He et al. (2015).

[b] Based on the study of Ng and Cheng (2012), and used in this study.

[c] Based on the study of Matzarakis et al. (1999).

Table 5

The resultant regression model shows the relationship between thermal comfort-based suitability score and factors representing user activity, weather type, and incoming solar radiation.

Predictor variable [a]	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	1.68e+0	1.03e-2	163.66	<.0001*	.
User activity [0.8 Met]	-1.00e+0	2.02e-2	-49.57	<.0001*	1.71
User activity [1.0 Met]	-8.02e-1	2.02e-2	-39.69	<.0001*	1.71
User activity [1.2 Met]	-6.20e-1	2.02e-2	-30.67	<.0001*	1.71
User activity [1.6 Met]	-4.49e-1	2.02e-2	-22.24	<.0001*	1.71
User activity [2.0 Met]	-2.53e-1	2.02e-2	-12.53	<.0001*	1.71
User activity [4.7 Met]	1.28e+0	2.02e-2	63.52	<.0001*	1.71
Weather Type [Cloudy]	-4.91e-2	1.23e-2	-3.99	<.0001*	1.79
Weather Type [Overcast]	-1.06e-2	1.50e-2	-0.71	0.481	1.85
Incoming solar radiation (W/m^2)	2.42e-3	2.95e-5	82.12	<.0001*	1.07

[a] Refer to Table 3 for the specific user activities with different levels of metabolic equivalent.

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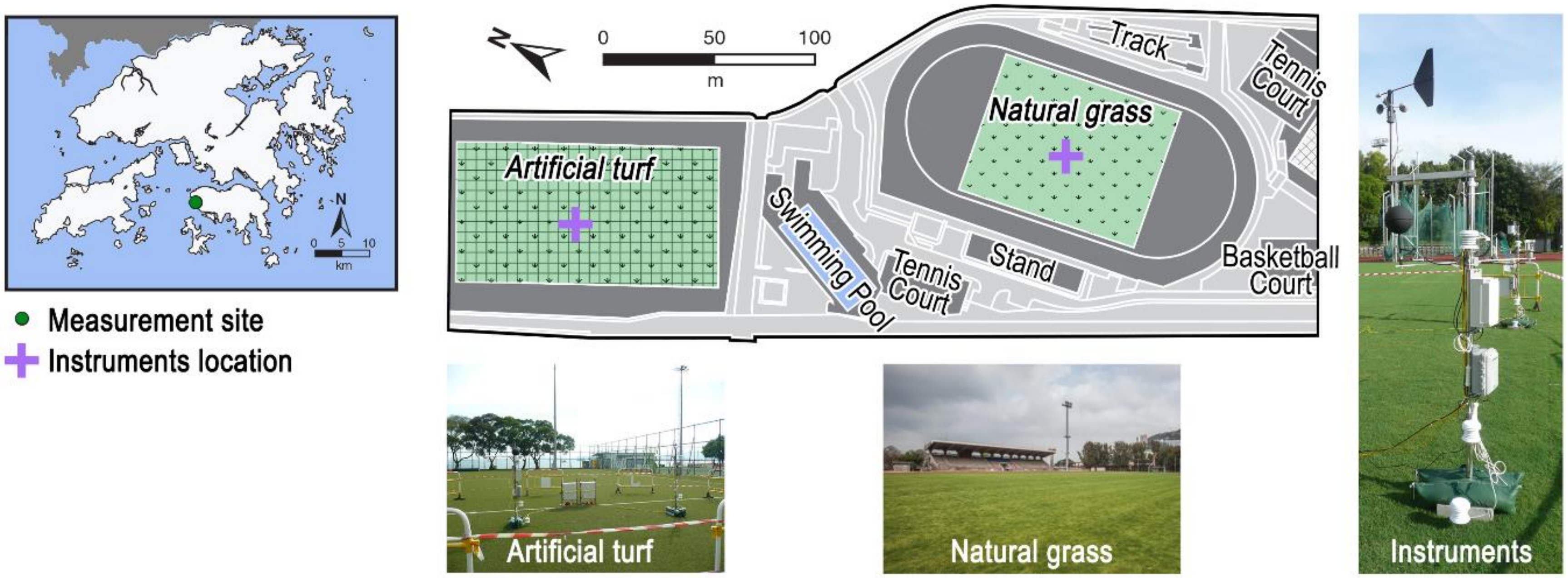
Acknowledgment

This research was supported by the Research Matching Grant Scheme awarded by the Hong Kong University Grants Council. The authors would like to thank Prof. Edward Ng and Dr. Zhixin Liu of the Chinese University of Hong Kong for their strong supports and insightful suggestions on this manuscript. We would like to thank the reviewers for their constructive comments and recommendations. We also thank the editor for handling our submission.

Developing a thermal suitability index to assess artificial turf applications for various site-weather and user-activity scenarios

Figures



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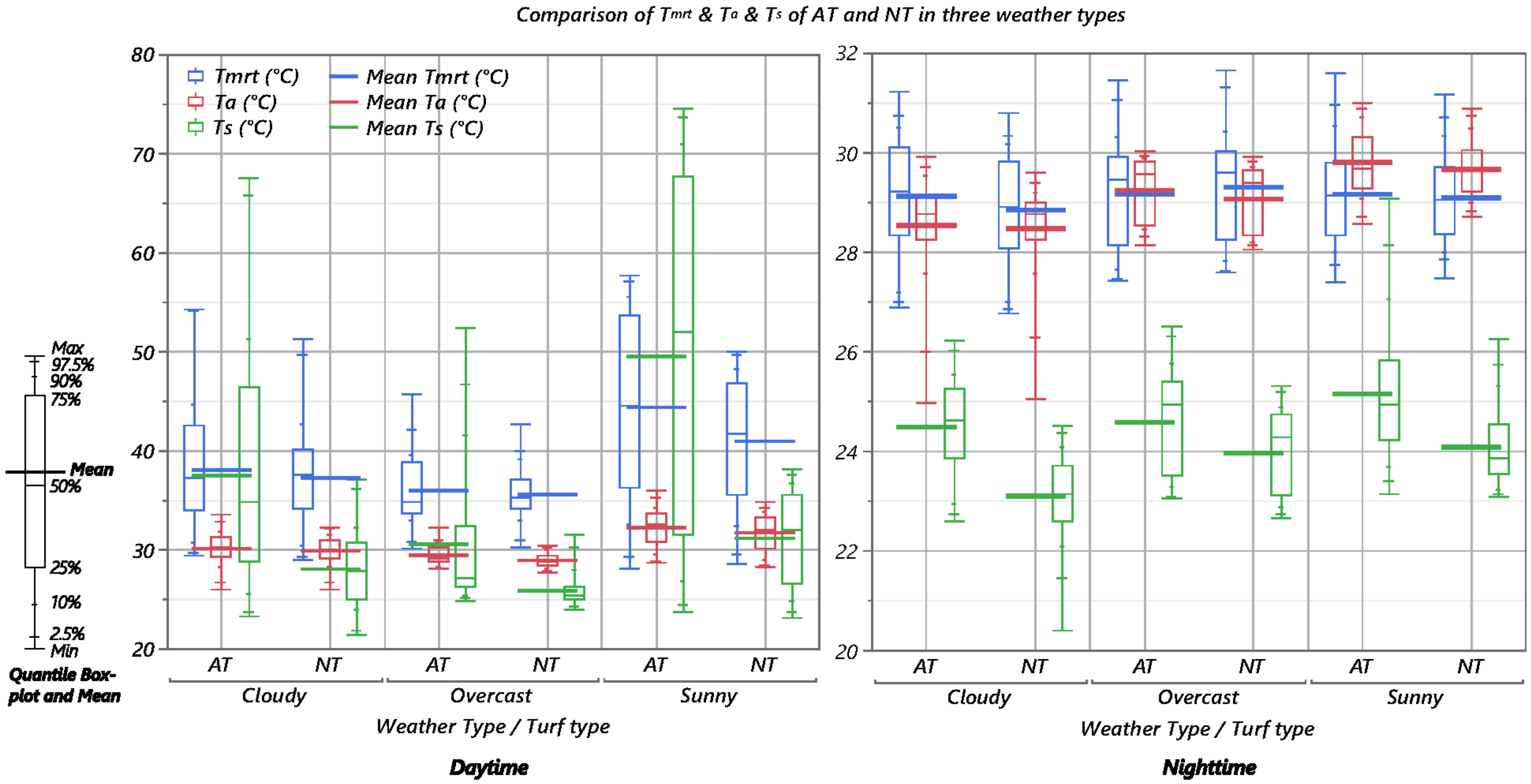

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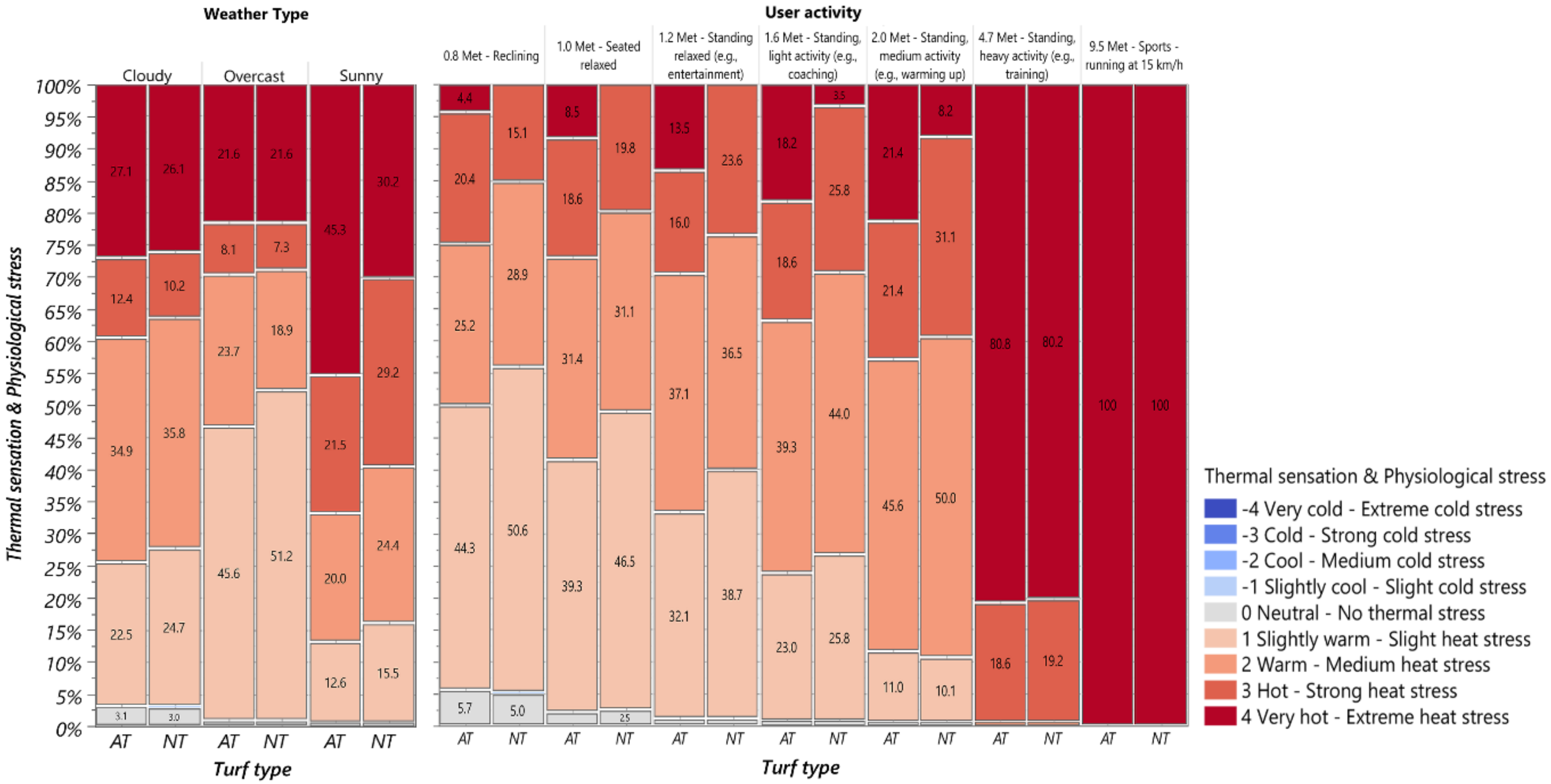

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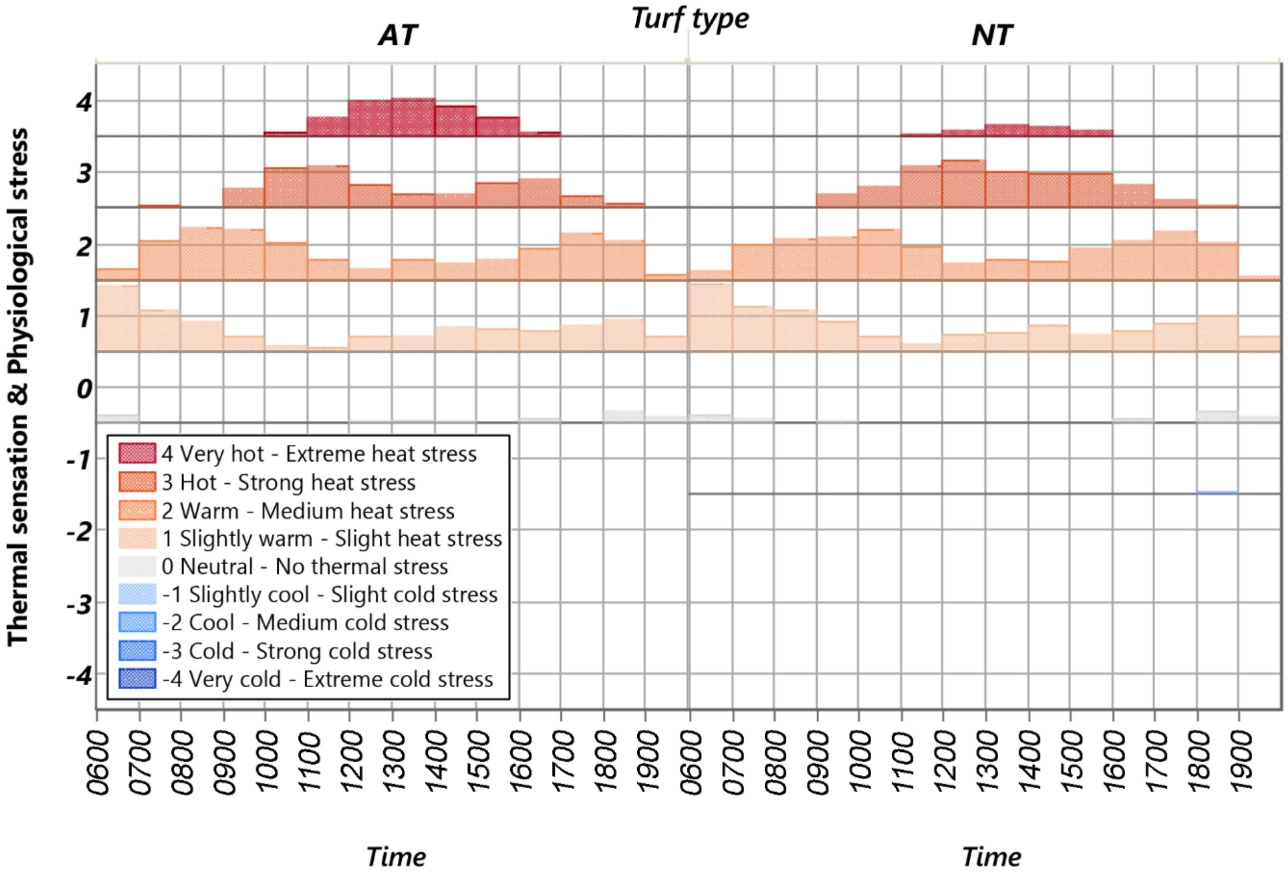

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CRediT authorship contribution statement

Yuan Shi Formal analysis, Writing - original draft

C.Y. Jim Conceptualization, Methodology, Investigation, Data curation, Writing - review & editing, Supervision, Funding acquisition