Impact of Reflective Roadways on Simulated Heat Strain at the Tokyo, Paris, and Los Angeles Olympics

Abstract

Purpose: Cities are applying reflective coatings on streets in an attempt to mitigate urban heat. These coatings are also being used to try to reduce heat stress during outdoor sports. This study models the progression of heat strain in elite marathon and race walk athletes competing on traditional dark asphalt, reflective pavement, or shaded asphalt in past and future Olympic Games (Tokyo (Sapporo), Paris, Los Angeles).

Methods: Observed weather (Sapporo) or expected climate conditions for each city, along with modeled mean radiant temperature (T_{MRT}) differences across the three surface types, were fed into the joint system (JOS-3) thermoregulation model. Resultant changes to heat strain parameters of core temperature (T_{cr}) and mean skin temperatures ($\bar{T}_{sk}$), as well as skin wettedness and cardiac output, were modeled.

Results: Reflective pavement slightly increased the average T_{MRT} (1.2–2.2°C), which caused higher overall radiant heat loads on athletes and thus slightly higher (yet insignificant) T_{cr} and $\bar{T}_{sk}$. These changes in simulated heat strain (worsening the situation) are the opposite of what is expected from a heat mitigation technology. Shading the athletes resulted in lower predicted T_{cr} (-0.37°C) and $\bar{T}_{sk}$ (-0.68°C) across events compared to sun-exposed asphalt, also decreasing cardiac output.

Conclusion: The minor increase in T_{MRT} over reflective pavement transferred a negligible difference in simulated athlete heat strain over a 2–3 hour intense competition. Overall, the large impact of solar radiation (even in the morning hours) should be decreased via design strategies that block the sun rather than strategies that increase radiant heat load.

Keywords: Heat strain; reflective pavement; thermal physiology; heat mitigation; core temperature; Olympics

Introduction

Pavement coatings on roads that reflect a higher amount of solar radiation are being piloted as a heat mitigation technique in numerous hot cities worldwide to reduce urban temperatures. The albedo-based reflective coatings, often called "cool pavements", are lighter in color (see example in **Figure 1**) and can reflect up to 38% of the sun's solar energy. This reflectivity is substantially higher than the 10–12% of solar radiation reflected from traditional darker seal coats (Schneider et al. 2023a). Thus far, Sydney, Tokyo, New Delhi, Phoenix, Doha, and Los Angeles have deployed these "cool" coatings on select roads. Multiple studies in such urban areas have demonstrated that the coatings indeed reduce the road surface temperature (T_{sfc})—or the "touch" temperature—by 0–9°C, depending on the time of day, year, and location (Kousis and Pisello 2023; Schneider et al. 2023a). However, studies have also shown that the additional reflected solar energy increases the mean radiant temperatures (T_{MRT}) (overall radiant heat load on people) midday above the lighter roadways compared to bare asphalt pavement (Erell et al. 2014; Middel et al. 2020). T_{MRT} is a critical metric used to quantify the exchange of radiant heat between a human and their surrounding environment based on incoming and outgoing short and longwave radiation in all directions (Guo et al. 2020; Vanos et al. 2021).

Studies in Phoenix and Los Angeles neighborhoods found that on hot days, the midday T_{MRT} was 2.3–5.1°C higher over "cool" (reflective) pavements, increasing the heat load on pedestrians (Middel et al. 2020; Schneider et al. 2023a). Simultaneously, studies thus far show that the coatings have little to no effect on T_{air} (averaging 0.3°C cooler at sunset) at pedestrian height (Schneider et al. 2023a). A higher daytime T_{MRT} with little change in T_{air} translates to a higher radiant load with little-to-no compensating convective cooling effect (Erell et al. 2014). Thus, the daytime use of reflective streets to walk, bike, or run would increase total heat loads over those in less reflective or shaded areas, which goes against improving active transport and recreational activities in cities (Turner et al. 2023). Further, it is well-known that radiation levels can have significant effects on perception (e.g., thermal comfort) as well as negative heat strain impacts (Otani et al. 2013, 2019, 2021; Vanos et al. 2017; Otani and Lee 2022).

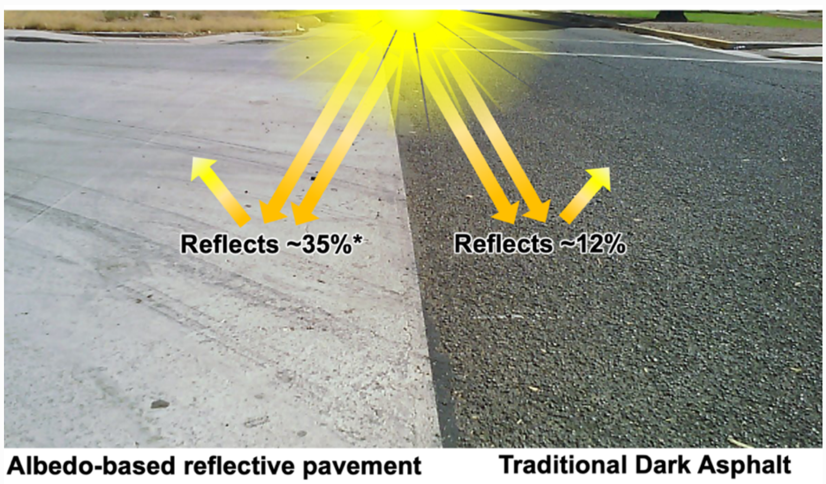

Figure 1: Example of fresh albedo-based reflective pavement seal (left) installed in Phoenix, Arizona, compared to traditional dark asphalt pavement (right). Photo credit: blinded for peer-review.

In contrast, depending on the type, height, size, and cover type, shade can reduce T_{MRT} up to 20–40°C compared to unshaded areas (Johansson and Emmanuel 2006; Makaremi et al. 2012; Kántor et al. 2018; Middel et al. 2021; Turner et al. 2023). This lower radiative load also reduces sweat production required to achieve heat balance (Guzman-Echavarria et al. 2023) and, therefore, the chances of dehydration and the associated cascade of heat illness.

Inspired by pilot deployments of reflective pavements by cities worldwide, discussions have arisen about applying reflective coatings in and around athletic areas for large-scale athletic championships, such as the Olympics. In preparation for the event, Tokyo installed 160 km of reflective surfaces (40% of the roads in central Tokyo) (Japanese Government 2016, 2022; Tokyo Shimbun 2023). Yet, at the cost of twice as much as traditional coatings in Japan (which is higher in other locations (City of Phoenix 2021)), and little to no decrease in T_{air}, the installation in Tokyo has come to a halt.

In Tokyo, the surface changes would have affected Olympic sports that use streets, including the marathon and race walk. Initially, the Tokyo marathon course intentionally included cooler routes shaded (by trees and buildings) and vegetated areas (Tokyo Shimbun 2023), yet still showed potentially dangerous conditions for athletes and spectators (Kosaka et al. 2018; Vanos et al. 2019). However, a more dramatic approach was taken to decrease the heat exposure to the athletes: the Tokyo Olympics marathon and race walk events were moved north to Sapporo. Nonetheless, major athletic events will occur in Tokyo, such as the yearly Tokyo marathon (although during a cooler time in March) and the World Athletic Championships in the Summer of 2025. Other cities, such as Los Angeles and Phoenix, continue installing reflective pavement for potential pavement preservation, hopeful reduction of the urban heat island (UHI), and related energy use declines. Yet those surfaces may not be the optimal choice in Los Angeles for Olympic sports in 2028. However, no study has evaluated the impact of a higher daytime radiative heat load due to reflective pavements on athletes' heat stress who spend several hours walking, running, or cycling on these roads to objectively evaluate the human impacts of reflective coatings. Athletes' heat strain and the consideration of factors like reflective coatings and local climatic conditions can be accurately estimated using validated individualized thermoregulation models (Havenith 2001; Oyama et al. 2023). This approach enables the estimation of heat illness risk without the need for direct experimentation on human subjects or athletes, ensuring a safe and ethical evaluation of potential mitigation strategies.

The purpose of this study is to compare the progression of simulated heat strain in elite athletes competing on traditional asphalt and reflective pavements during recent and future Olympics, including Sapporo, Japan (2020 Olympics, held August 2021), Paris, France (2024 Olympics), and Los Angeles, United States (2028 Olympics). The heat stress impact on predominantly shaded routes is also modeled in all cities. We hypothesize that during the race times (morning hours) and days of these events, an athlete's overall heat load will not change, which is expected due to the tradeoff (a lower emitted radiation but higher reflected radiation) when comparing the reflective pavement to traditional (or conventional) dark asphalt pavement. We also hypothesize lower estimated heat strain in athletes if performing in predominantly shaded locations on traditional asphalt. Microclimate simulations are run based on observed or expected hourly local weather conditions in the three Olympic cities. These data are then fed into a rigorously validated thermoregulation model—JOS-3—that considers the various anthropometric characteristics, clothing, metabolic rate, and sex of the athletes (Takahashi et al. 2021). Events of focus include the men's and women's marathons in all cities and the men's 50km race walk in Sapporo.

Some studies have monitored local microclimates to determine heat stress or input results into thermal indices or thermal comfort models (*e.g.,* DeMartini et al. 2014; Honjo et al. 2018; Vanos et al. 2019; Thorsson et al. 2020), which are simpler/more accessible to use yet are not purposed for dynamic sports as some models do not allow for the alteration of metabolic rate, sex, body shape, and/or clothing (Grundstein and Vanos 2020). Few studies (e.g., Rida et al. 2023a) have combined real-world urban microclimatic simulations or data with 3-dimensional models of human thermoregulation (Joshi et al. 2022; Xu et al. 2023); the use of these models is more common with thermal chamber data (e.g., Jia et al. 2023; Rida et al. 2023b; Zhang et al. 2023). Thus, methods herein are novel in coupling observed and simulated urban climate data with an advanced model of human thermoregulation that can consider individuals' anthropometric details, sex, metabolic rate, and a wide range of environmental conditions.

Methods

Climate Conditions

Weather inputs for the simulations include T_{air}, dew point (T_d), relative humidity (RH), and solar radiation levels within each city at hourly resolution. For Sapporo, we used observed weather data (**Table 1**) from the Sapporo airport (42.779°N, 141.687°E) based on the start time and period of each event (men's and women's marathons and men's 50km race walk)—see **Table 1**. For Paris, weather estimates (T_{air}, T_d, and RH hourly climate normals) for the dates of Aug 10 and 11 (marathon dates) were obtained from the National Center for Environmental Information (NCEI) from the Montsouris station (48.8231°N, 2.3367°E), calculating climate averages for 2005–2022. For Los Angeles, the approach used was similar to Paris, yet because the exact dates and times are not known, we used averages for the dates between July 15 and 30 in the morning hours (7:00 am start) for 2005–2020 using HadISD.3.3.0-global sub-daily station dataset version v331_202301p (Dunn et al. 2016; Dunn 2019).

Solar radiation data were downloaded from the National Solar Radiation Database (NSRDB) for all locations based on data availability (Sengupta et al. 2018), accessible at https://nsrdb.nrel.gov/data-viewer. Average estimates for the given dates/times of year (**Table 1**) of global horizontal irradiation (GHI), direct normal irradiation (DNI), and diffuse horizontal irradiation (DHI) for Sapporo are from NSRDB-Himawari 2011–2020 data, for Paris from NSRDB-METEOSTAT 2017–2019 data, and for Los Angeles are from NSRDB-Americas 1998–2022 data.

Mean Radiant Temperature Modeling

The solar and longwave radiation variables encompassing T_{MRT} are not commonly available from weather stations. Because of the level of detail required to test the influence of regular/conventional and reflective road surfaces that are sun-exposed and shaded, we modeled T_{MRT} using SOLWEIG V1.0 equations (Lindberg et al. 2008) for the simplified case of an open space or road (sky view factor, SVF =1) as well as a more narrow urban canyon (SVF=0.4) with shading largely from buildings, as in many large cities. Therefore, three T_{MRT} values were calculated: sun-exposed asphalt (A_S) pavement, sun-exposed reflective pavement, and A_S pavement in a shaded urban canyon. SOLWEIG V1.0 code was implemented using

Python V3.10.9, with modifications to differentiate albedo (α) values from the ground (α A_S road = 0.12, α reflective road = 0.35) and wall albedo (α buildings = 0.15) and T_{sfc} estimates. We used a system of mathematical equations to obtain T_{sfc} (see **Supplemental Information (SI)**) solving a surface energy surface balance for urban areas (Oke et al. 2017), with heat storage calculation using the Objective Hysteresis Model (Grimmond et al. 1991) assuming coefficients for an asphalt surface (Asaeda and Ca 1993). The emissivity of all surfaces was set at 0.96 and the Bowen ratio at 5.

Table 1: Hourly weather conditions[1] measured in Sapporo, as well as climate conditions expected based on time of day and year for Paris and Los Angeles. LST: Local Standard time; T_{air}: air temperature; RH: relative humidity; T_{dew}: Dew point temperature; P_{air} (vapor pressure, kPa); GHI: Global Horizontal Radiation.

	Location	**Date**	**Time (hr) (LST)**	**T_{air} (°C)**	**T_{dew} (°C)**	**RH (%)**	**P_{air} (kPa)**	**Windspeed[2] (m/s) at 1.5m**	**GHI[3] (W/m^2)**
Women's Marathon	Sapporo	7-Aug-2021	6:00	26.0	22.0	79.0	2.65	2.72	197.6
			7:00	27.0	21.0	70.0	2.49	4.60	327.9
			8:00	28.0	22.0	67.0	2.65	3.97	471.2
			9:00	29.0	22.0	66.0	2.65	4.60	597.7
Men's Marathon	Sapporo	8-Aug-2021	7:00	26.0	22.0	79.0	2.65	3.14	292.2
			8:00	26.0	22.0	76.0	2.65	3.55	440.3
			9:00	27.0	22.0	73.0	2.65	5.43	502.8
			10:00	27.0	22.0	75.0	2.65	5.02	580.8
Men's 50km Race Walk	Sapporo	6-Aug-2021	5:00	25.0	22.0	83.0	2.65	0.84	39.4
			6:00	26.0	22.0	81.0	2.65	0.84	128.9
			7:00	27.0	22.0	73.0	2.65	1.46	277.6
			8:00	29.0	23.0	68.0	2.81	1.46	365.6
			9:00	31.0	23.0	65.0	2.81	1.89	510.0
Women's Marathon	Paris	11-Aug-2024	8:00	19.0	12.6	66.4	1.46	1.53	460.1
			9:00	20.2	12.5	61.2	1.45	1.71	463.0
			10:00	21.2	12.3	57.2	1.43	2.01	537.0
			11:00	22.2	12.1	52.8	1.41	2.03	548.8
			12:00	23.1	12.3	50.6	4.13	2.04	653.0
Men's Marathon	Paris	10-Aug-2024	8:00	19.9	12.9	64.1	1.49	1.83	292.8
			9:00	20.9	12.4	58.3	1.44	2.16	403.8
			10:00	21.9	12.5	55.2	1.45	2.31	500.8
			11:00	22.7	12.2	51.5	1.42	2.46	498.8
			12:00	23.7	12.1	48.2	1.41	2.51	520.2
Either Marathon event[4]	Los Angeles	15-Jul through 30-Jul-2028	8:00	21.7	16.5	72.2	1.88	0.96	520.2
			9:00	23.0	18.7	66.9	2.16	1.34	713.7
			10:00	23.9	16.5	63.2	1.88	1.96	864.6
			11:00	24.7	16.4	59.8	1.87	2.39	948.3

[1]Data Sources - *Sapporo:* Sapporo airport (42.779°N, 141.687°E); *Paris*: Montsouris station (48.8231°N, 2.3367°E) via NCEI; *Los Angeles:* HadISD.3.3.0- global sub-daily station dataset version v331_202301p (Dunn et al. 2016; Dunn 2019).
[2]Windspeed is often measured at 10 m height at first-order weather stations. We used the log-wind equation to bring the wind speed down to human height based on surface roughness (Jacobson 2005). This involves accounting for the roughness of the surface, which decreases the windspeed closer to the surface, based on the log-wind equation by Stull (2015) (equation 18.14b) assuming a surface roughness of 0.03m.
[3]From the National Solar Radiation Database (NSRDB) for all locations based on data availability (Sengupta et al. 2018) accessible at https://nsrdb.nrel.gov/data-viewer.
[4]Day and exact times of the marathons are not yet set; therefore, we used average climate data across the two weeks in the given time windows.

Heat Strain Modeling

Thermoregulatory responses of athletes were simulated through the joint system (JOS-3) thermoregulation model (Takahashi et al. 2021) as it allows the modeling of individual anthropometric characteristics and sex of athletes representing different sports (**Table 2**). The JOS-3 thermoregulation model was validated in detail for intense activities (high metabolic rate), climatic conditions, and various anthropometric characteristics (Oyama et al. 2023), which are required for the current study. The model segments the human body into 17 parts, consisting of 85 nodes, including core, muscle, fat, skin, artery, vein, superficial vein, and central blood pool. The generalized equation for heat balance for all tissues (core, muscle, fat, skin, artery, vein, superficial vein, and central blood pool) is expressed in Eqn. 1.

$$C_{j,i}\frac{\mathrm{dT_{j,i}}}{dt} = Q_{bm\,j,i} + Q_{work\,j,i} + Q_{sh\,j,i} + Q_{nst\,j,i} + Q_{bf\,j,i} - Q_{cond_{j-j',i}} - Q_{sensible_{sk,i}} - Q_{latent_{sk,i}} - Q_{resp_{cr,chest}} \qquad (1)$$

where C is heat capacity $\left(\frac{J}{K}\right)$, T is temperature of a given node (K), t is time (s), Q_{bm} is basal metabolic heat generation (W), Q_{work} is heat generated due to external work/activity (W), Q_{sh} is heat generated due to shivering thermogenesis (W), Q_{nst} is heat generated due to non-shivering thermogenesis (W), $Q_{cond_{j-j'}}$ is conductive heat transfer between two successive nodes $(j-j')(W)$, $Q_{sensible_{sk}}$ is sensible (convective + radiative) heat transfer (W), $Q_{latent_{sk}}$ is latent (sweat evaporation) heat transfer (W), $Q_{resp_{cr,chest}}$ is heat loss due to respiration from the chest (W), i represents the body part, and j represents the node.

Basal metabolic heat is defined as the function of height, weight, and age for male and female athletes as described in Eqns. 2 and 3, respectively (Harris and Benedict 1918; Roza and Shizgal 1984). The heat production in individual body parts due to external work/activity is expressed by Eqn. 4 (Takahashi et al. 2021).

$$Q_{bm} = (88.36 + 500.3 \cdot ht + 13.40 \cdot wt - 5.68 \cdot age) \cdot 0.048 \qquad \text{(for male)} \qquad (2)$$

$$Q_{bm} = (447.59 + 479.9 \cdot ht + 9.25 \cdot wt - 4.33 \cdot age) \cdot 0.048 \qquad \text{(for female)} \qquad (3)$$

$$Q_{work_i} = Q_{work_{f_i}}(PAR - 1) \cdot Q_{bm} \qquad (4)$$

$$Q_{bf_i} = 1.067 \cdot BF_{j'-j} \cdot (\mathrm{T_{j'}} - T_j) \qquad (5)$$

$$Q_{resp_{cr,chest}} = \big(0.0014 \cdot (34.0 - T_{air}) + 0.0173 \cdot (5870 - P_{air})\big) \cdot Q_{total_i} \qquad (6)$$

where, ht is height (m), wt is weight (kg), age is age of human subject $(years)$, $Q_{work_{f_i}}$ is distribution coefficients of heat produced by external work $(-)$, PAR is physical activity ratio $(-)$, $BF_{j'-j}$ is blood flow from j' to j $\left(\frac{l}{h}\right)$, T_{air} is air temperature $(°C)$, and P_{air} is water vapor pressure (Pa).

The influence of clothing on sensible and latent heat exchange is calculated based on intrinsic thermal resistance $\left(R_{c_{cl}}\right)$ and intrinsic evaporative resistance $\left(R_{e_{cl}}\right)$, represented by Eqns. 7 and 8, respectively:

$$Q_{sensible_{sk,i}} = \left(R_{c_{cl_i}} + \frac{1}{f_{cl_i}\left(h_{c_i}+h_{r_i}\right)}\right)^{-1} \left(T_{sk,i} - T_{o_i}\right) SA_i \quad (7)$$

$$Q_{latent_{sk,i}} = w_i \left(R_{e_{cl_i}} + \frac{1}{f_{cl_i} L_R h_{c_i}}\right)^{-1} \left(P_{sat_{sk,i}} - P_{air}\right) SA_i \quad (8)$$

where, h_{c_i} is convective heat transfer coefficient $\left(\frac{W}{m^2K}\right)$, h_{r_i} is radiative heat transfer coefficient $\left(\frac{W}{m^2K}\right)$, $T_{sk,i}$ is skin temperature (K), T_{o_i} is operative temperature (K), $P_{sat_{sk,i}}$ is saturation pressure of water vapor at the skin (Pa), P_{air} is water vapor pressure of air (Pa), $\mathrm{R}_{\mathrm{c}_{\mathrm{cl_i}}}$ is intrinsic thermal resistance of clothing ensemble $\left(\frac{m^2K}{W}\right)$, $\mathrm{R}_{\mathrm{e}_{\mathrm{cl}_i}}$ is intrinsic evaporative resistance of the clothing ensemble $\left(\frac{m^2Pa}{W}\right)$, $\mathrm{f}_{\mathrm{cl_i}}$ is clothing area factor $(-)$, SA_i is surface area of skin (m^2), and $\mathrm{w_i}$ is skin wettedness $(-)$.

We focus our evaluation on simulated heat strain outputs of core temperature, skin temperature, skin wettedness, and cardiac output. Core temperature is a fundamental indicator of body's thermal state reflecting the net heat storage or dissipation rate given the overall environment and person characteristics (Bouchama et al. 2022). Skin temperature and skin wettedness helps in understanding the body's heat dissipation through convection, radiation, and evaporation. Similarly, physiological research confirms that skin wettedness is also a critical for comfort, perception, and heat stress (Vargas et al. 2020). Finally, cardiac output indicates increased cardiovascular demands imposed by heat stress by redistributing blood flow to the skin for heat dissipation. These variables provide a comprehensive analysis of heat strain to isolate radiative and thermal impacts.

Model Inputs

The maximum race speeds of marathon runners showed a direct correlation with BMI, with optimal values of 19.80 $\frac{kg}{m^2}$ and 18.20 $\frac{kg}{m^2}$ for male and female athletes, respectively (Marc et al. 2014). The average body mass for male and female marathon runners was considered as 56.20 kg and 48.30 kg, respectively (Marc et al. 2014; Racinais et al. 2021). For male 50 km race walkers, the average weight and height were assumed to be 66.40 kg and 1.77 m (Gomez-Ezeiza et al. 2018). As described in **Table 2**, analyses were performed for the average values of weight, height, metabolic rate, and race duration to analyze the impact of reflective roadways on athletes' heat strain. Intrinsic thermal and evaporative resistances of the clothing ensemble were assumed to be 0.05 $\frac{m^2\,K}{W}$ and 10.00 $\frac{m^2\,Pa}{W}$ for covered body parts (chest, back, upper arm, thigh, and feet) (ISO9920 2007). The maximum oxygen consumption for male and female marathon runners was assumed to be 53.40 $\frac{ml\,O_2}{kg\,min}$ and 43.60$\frac{ml\,O_2}{kg\,min}$, leading to energy expenditures of 40.48 $\frac{ml\,O_2}{kg\,min}$ (11.56 MET) for males and 33.05 $\frac{ml\,O_2}{kg\,min}$ (9.44 MET) for females (Noakes et al. 1991; Malek et al. 2004). The average energy cost for race walkers, based on measurements by Farley and Hamley (1978), was 27.0 $\frac{kJ}{\min m^2}$ (7.70 MET). Environmental parameters, available at a frequency of 1 hr, underwent linear/polynomial fitting to resample to 20-minute intervals.

Table 2: Attributes and assumptions for modeling athletes in three events within the JOS-3 thermoregulation model.

Assumptions	Marathon (male)	Marathon (female)	Race-walk (Male)
Weight *[kg]*	56.20[1]	48.30[2]	66.40[3]
Height *[m]*	1.68[1]	1.63[1]	1.77[3]
$R_{c_{cl}}$[4] $\left[\frac{m^2K}{W}\right]$	0.05	0.05	0.05
$R_{e_{cl}}$[4] $\left[\frac{m^2Pa}{W}\right]$	10.00	10.00	10.00
METs/PAR [met]	11.56[5]	9.44[5]	7.70[6]
Environmental Parameters	*Table 1*	*Table 1*	*Table 1*
Race Duration[7] [HH:MM]	02:15	02:30	04:11

[1]Marc et al. (2014); [2]Racinais et al. (2021); [3]Gomez-Ezeiza et al. (2018); [4]ISO9920 (2007); [5]Noakes et al. (1991), Malek et al. (2004); [6]Farley and Hamley (1978); [7]Arcelli (1996).

Analysis

Observed weather data for Sapporo and local climate norms for Paris and Los Angeles (**Table 1**) were input into the SOLWEIG V1.0 (Lindberg et al. 2008) model equations coded in Python V3.10.9 to determine differences in microclimatic variables that runners or walkers would experience in the morning hours along roadways for their given events. The JOS-3 open-source thermoregulation model used for heat strain analysis used Python V3.11. The data processing and graphs were prepared using Python V3.11.5 and Inkscape ("The Inkscape Project"). All differences compare reflective coatings or shaded asphalt surfaces in urban canyons to the sun-exposed asphalt pavement results as a baseline.

Results

Overview

Here, we determine if reflective, or "cool", pavement helps decrease simulated heat strain in elite marathon and race walk athletes compared to traditional asphalt pavement, modeled for recent and future Olympic marathon or race walk settings in Sapporo, Japan; Paris, France; and Los Angeles, United States. We applied a mixed-modeling approach using weather data and microclimatic modeling fed into a human thermoregulation model to determine variations in the estimated heat strain in three situations: over sun-exposed traditional asphalt (A_S); over sun-exposed reflective pavement; over traditional A_S within urban canyon providing shade, assuming SVF = 0.4.

Microclimate Variations by Surface Type & Shade Presence

Observed weather data for Sapporo and local climate norms are provided in **Table 1**. The T_{mrt} in Sapporo was, on average, 1.9±0.73°C, 2.2±0.51°C, and 1.2±0.78°C higher over reflective pavement for the Women's marathon, Men's marathon, and Men's 50 km race walk, respectively (**Table 3**). These differences increase with the sun's position in the sky, reaching a maximum difference of 2.7°C at the end of the race (9:00 or 10:00 am). In Paris, the T_{MRT} is estimated to be ~2.1°C higher over the reflective pavement during the marathon race times, on average, with values also increasing throughout the morning. Finally, based on the time of year and an expected morning race time, the T_{mrt} in Los Angeles is estimated to be 3.2±0.84°C higher on a reflective surface, reaching a maximum difference of 4.1°C by 11:00 am (which would be higher as the solar angle increases) (**Table 3**). Both Paris and Los Angeles exhibit higher solar radiation at the given times of year and day compared to Sapporo, thus explaining the higher differences. These higher T_{mrt} values over reflective pavement translate into higher values of radiative heat gain to a human walking or running on said surface.

Table 3: Results of mean radiant temperature ($\boldsymbol{T_{mrt}}$) values and differences in an open area (SVF = 1.0) traditional asphalt pavement (albedo 12%) versus reflective pavement in an open area (albedo 35%) and shaded asphalt pavement (SVF= 0.4, or narrow urban canyon). LST: Local Standard Time.

	Location	**Date**	**Time (hr) (LST)**	**T_{mrt} (°C) asphalt (As), open**	**T_{mrt} (°C) reflective pavement, open**	**ΔT_{mrt}: RP−As (°C)**	**T_{mrt} (°C) shaded urban canyon, As**	**ΔT_{mrt}: Shaded As – Open As (°C)**
Women's Marathon	Sapporo	7-Aug-2021	6:00	44.4	45.4	1.0	31.0	-13.3
			7:00	49.5	51.1	1.7	35.0	-14.4
			8:00	57.0	59.2	2.2	40.3	-16.7
			9:00	62.6	65.3	2.7	45.3	-17.3
			Mean±SD	**53.3±8.04**	**55.3±8.77**	**1.9±0.73**	**37.9±6.19**	**-15.4±1.88**
Men's Marathon	Sapporo	8-Aug-2021	7:00	47.6	49.1	1.5	34.2	-13.4
			8:00	55.8	57.9	2.1	39.4	-16.5
			9:00	61.0	63.4	2.4	44.3	-16.7
			10:00	63.6	66.3	2.7	47.0	-16.6
			Mean±SD	**57.0±7.05**	**59.2±7.55**	**2.2±0.51**	**41.2±5.63**	**-15.8±1.61**
Men's 50km Race Walk	Sapporo	6-Aug-2021	5:00	29.1	29.3	0.2	24.7	-4.4
			6:00	38.5	39.2	0.6	29.1	-9.5
			7:00	46.5	47.8	1.3	33.6	-13.0
			8:00	52.9	54.5	1.6	39.3	-13.6
			9:00	58.1	60.3	2.2	43.8	-14.3
			Mean±SD	**45.0±11.5**	**46.2±12.30**	**1.2±0.78**	**34.1±7.66**	**-10.9±4.11**
Women's Marathon	Paris	11-Aug-2024	8:00	53.9	55.8	2.0	34.8	-19.0
			9:00	52.8	54.9	2.0	35.7	-17.1
			10:00	61.3	63.5	2.3	42.4	-18.9
			11:00	63.5	65.8	2.3	45.2	-18.3
			12:00	66.4	69.1	2.6	48.0	-18.4
			Mean±SD	**59.6±5.99**	**61.8±6.24**	**2.2±0.26**	**41.2±5.82**	**-18.3±0.73**
Men's Marathon	Paris	10-Aug-2024	8:00	44.7	46.1	1.4	31.3	-13.4
			9:00	54.1	55.9	1.8	37.6	-16.5
			10:00	60.0	62.1	2.2	42.0	-17.9
			11:00	61.3	63.5	2.2	44.1	-17.2
			12:00	58.7	61.0	2.3	43.4	-15.3
			Mean±SD	**55.8±6.67**	**57.7±7.10**	**2.0±0.36**	**39.7±5.33**	**-16.1±1.78**
Marathons	Los Angeles	15-Jul through 30-Jul-2028	8:00	53.0	55.2	2.2	36.4	-16.6
			9:00	58.2	61.1	2.9	42.1	-16.1
			10:00	60.3	63.9	3.6	46.2	-14.1
			11:00	59.3	63.4	4.1	48.5	-10.8
			Mean±SD	**57.7±3.23**	**60.9±3.99**	**3.2±0.84**	**43.3±5.31**	**-14.4±2.63**

Simulated Athlete Heat Strain

We modeled the heat strain parameters of predicted core temperature (T_{cr}) (**Figure 2**) and predicted mean skin temperature ($\bar{T}_{sk}$) (**Figure 3**) for the seven simulated races. The average absolute changes for reflective pavement and shade throughout the races compared to sun-exposed As pavement are provided in **Figure 4**. At the end of the race, reflective pavement displayed a negligible effect on the simulated T_{cr} (0.05°C) and $\overline{T}_{sk}$ (0.09°C), on average, across the running and walking events modeled in the three cities (**Figure 4**). Differences are lower for women than men. Shaded asphalt pavement surfaces result in a lower T_{cr} (-0.37°C) and $\overline{T}_{sk}$ (-0.68°C), on average, across the events. While these are reduced, they are minor for overall heat safety given the multitude of other parameters affecting the estimated heat strain, particularly metabolic intensity.

In assessing the athletes' experience in the Sapporo marathons and race-walk, the women's race being moved to an hour earlier supported lower T_{cr} values in the oppressively humid conditions of the city. If the entire routes were more shaded for these events, based on a 40% sky view factor modeled here, it is estimated that T_{cr} would be -0.28°C, -0.29°C, and -0.41°C lower for the women's marathoners, men's marathoners, and men's racewalker, respectively, compared to fully sun-exposed asphalt (**Figure 4**). Similarly, the $\overline{T}_{sk}$ would have been lowered by 0.60°C, 0.54°C, and 0.72°C in these shaded conditions versus open asphalt in Sapporo.

Looking to future events in Paris and Los Angeles, the lower T_{air} and RH expected in Paris compared to Sapporo and Los Angeles shows less heat strain expected for the athletes in Paris if the weather that day follows the normal climatology. These differences are provided across the graphs yet are most apparent in **Figure 4**. The 2028 expected conditions in Los Angeles (assuming a start time of 8:00 am) are concerning for the athletes given the Los Angeles climatology during the planned two weeks. Using reflective pavement in Los Angeles would *increase* estimated T_{cr} on average by ~0.08°C and 0.10°C and $\overline{T}_{sk}$ by 0.14°C and 0.15°C compared to open traditional asphalt for women's and men's marathoners, respectively. However, if Los Angeles plans a shaded route for that time of day or adds shade for the runners throughout the course, the estimated T_{cr} would -0.36°C and -0.43°C lower for women and men, respectively, with respective $\overline{T}_{sk}$ reductions reaching -0.67°C and -0.70°C (**Figure 4**). Paris would see slightly greater reductions in both $\overline{T}_{sk}$ and T_{cr} if the entire racecourse is shaded, which would occur due to the greater T_{mrt} reduction (-19°C in shade) during the Paris women's marathon compared to the other races (**Table 3**). Differences among the cities also depend on the sun angle at the time of year and day for the location, where the sun will hit runners more perpendicular to the body in the morning in Paris at the given latitude (48.8°N) than in Los Angeles (34.0°N). Thus, potential improvements for athletes due to shade are also greater in Paris.

In line with T_{cr} and $\overline{T}_{sk}$ results, the reflective pavement has negligible negative or positive impact on skin wettedness, resulting in a ~0.002 change (or 0.2%) (see **SI**). Conversely, shade provides a minor positive impact on skin wettedness (w_{sk}), lowering w_{sk} by 0.02 change (or 2%). Consistent with the potential negative effects of reflective pavement on T_{cr} and $\overline{T}_{sk}$, cardiac output also increases with athletes running over reflective pavement (on average, 13 $\frac{l}{h}$ higher or ~1%). In contrast, shade provides a considerable positive impact on the cardiac output of athletes, with an average reduction of 91.18 $\frac{l}{h}$ or ~5.0%.

Overall, along with the T_{mrt}, the T_{air}, RH, and windspeed can also considerably affect the total estimated heat strain. Thus, a key takeaway of the results involves these differences in modeled heat strain found by location and time of day. There are notably higher values of T_{cr} as a product of Sapporo and Los Angeles weather compared to Paris, or more oppressive conditions expected based on the climatology of August

11 compared to August 10 in Paris (**Table 1**). Further, as the impact of solar radiation on heat load, even in the morning hours, is high due to higher angles of sun incidence to people (sunbeam hits a greater surface area close to sunrise/sunset), these results show that incoming radiation to athletes should be decreased via design (buildings, tree, built shade), not increased. However, when the weather is expected to be oppressively hot, organizers should also be prepared to move events to earlier in the morning, as in Sapporo, for the women's marathon.

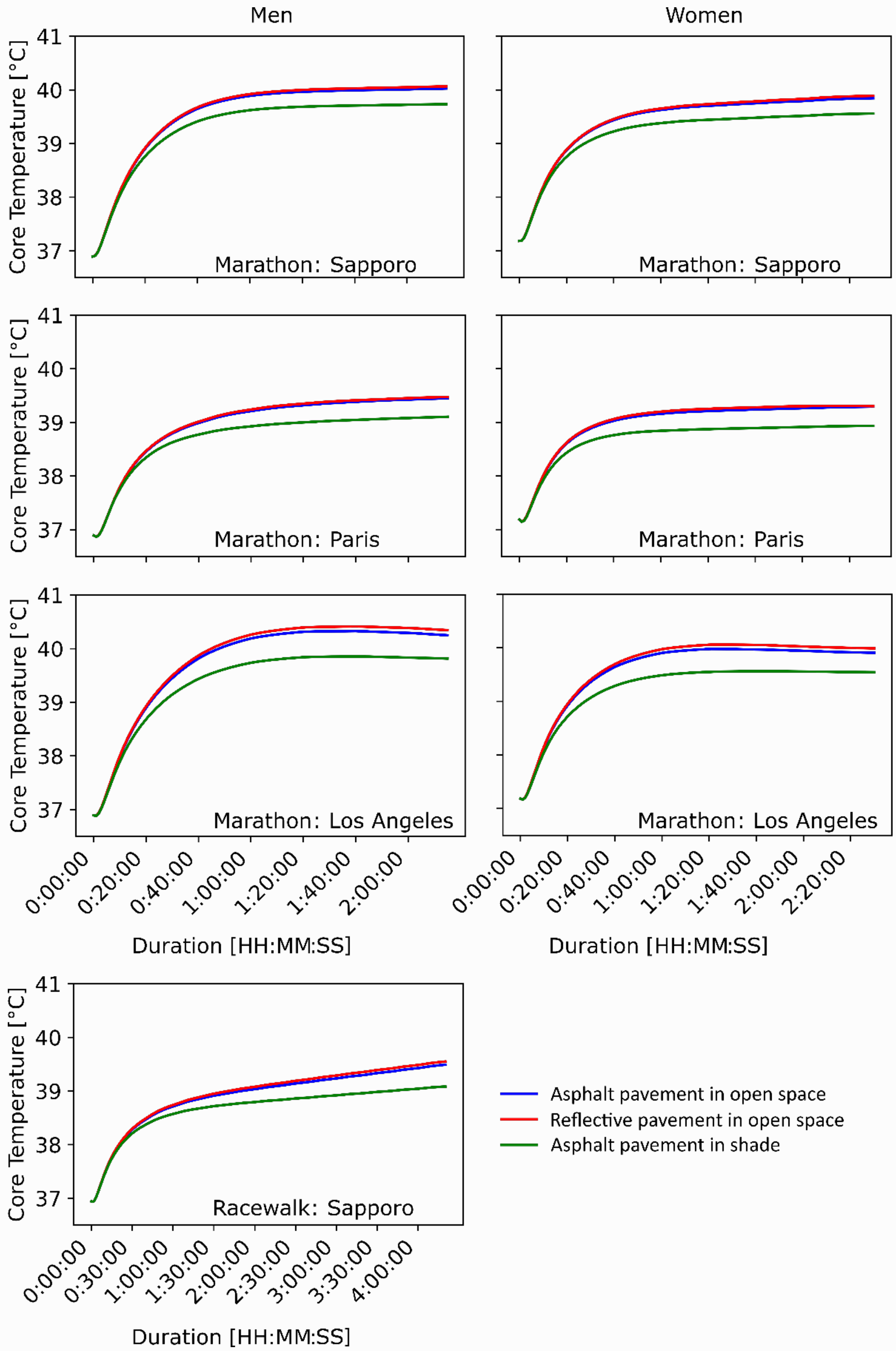

Figure 2. Simulated core temperature of men and women athletes across various Olympic events and surface types: asphalt pavement in an open space (blue), reflective pavement in an open space (red), and asphalt pavement with shade in a narrow urban canyon (green).

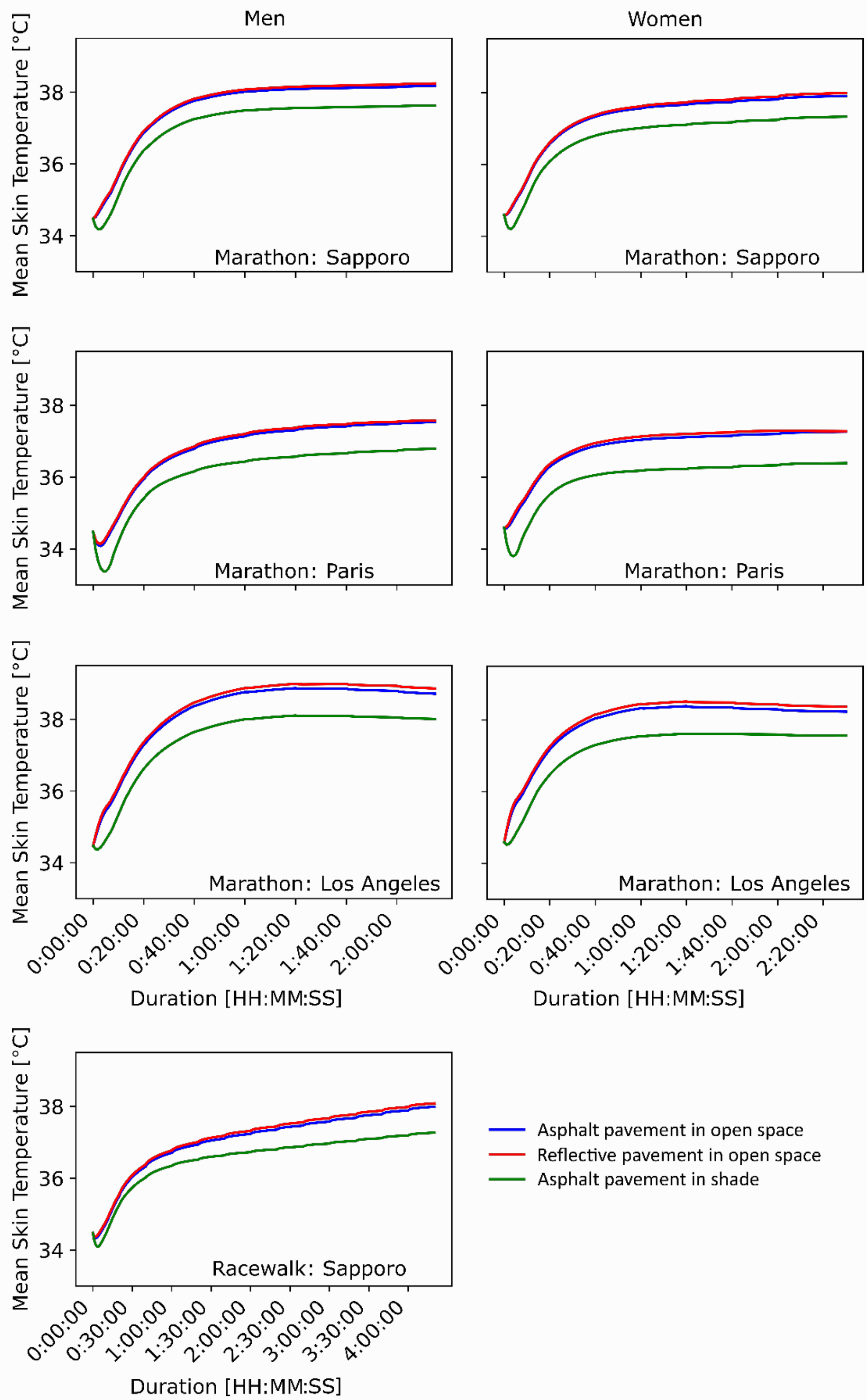

Figure 3. Simulated mean skin temperature of men and women athletes across various Olympic events and surface types: asphalt pavement in an open space (blue), reflective pavement in an open space (red), and asphalt pavement with shade in a narrow urban canyon (green).

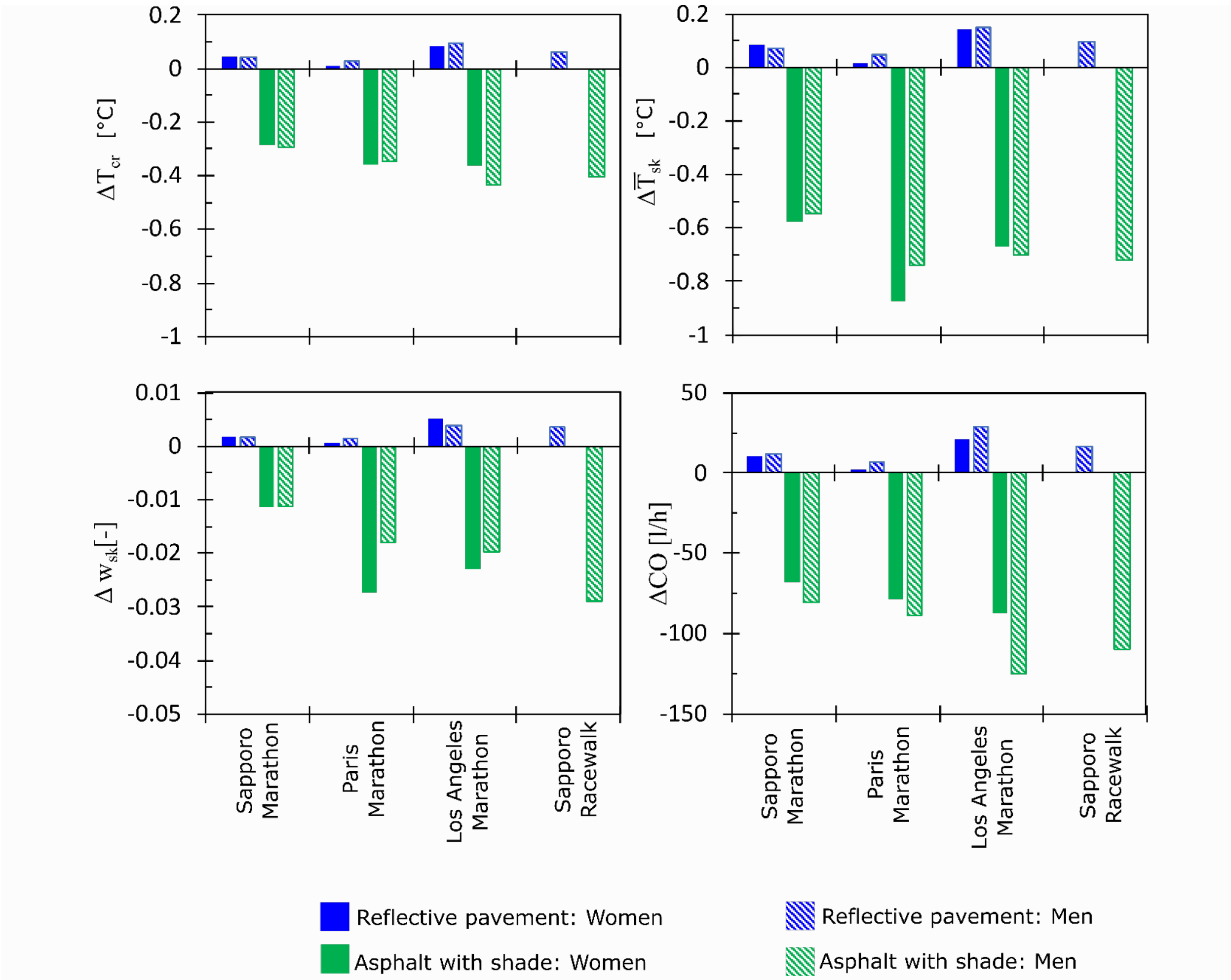

Figure 4. Effect of sun-exposed reflective pavement and shaded asphalt pavement compared to sun-exposed traditional asphalt on core (T_{cr}), mean skin temperature ($\overline{T}_{sk}$), skin wettedness (w_{sk}), and cardiac output (CO). A value of 0 indicates no change from traditional asphalt in an open space. Negative values indicate reductions due to shade.

Discussion

With numerous major sporting events occurring during warm or hot weather, and with climate change and urban-induced warming fueling increased occurrence of extreme heat (Georgescu et al. 2014; Krayenhoff et al. 2018), the reduction of heat exposure is an increasingly critical issue for athlete performance and health (Hosokawa and Vanos 2020; Flouris et al. 2021; Mantzios et al. 2022). Here, we report a new approach coupling urban microclimate and human thermoregulation modeling to determine the impact of two well-known heat mitigation strategies—reflective pavement and shade—on the simulated heat strain of athletes competing in marathon and 50 km race-walk events in past and future Olympics (Sapporo, Paris, Los Angeles). This approach integrates well-established and fundamental principles from urban micrometeorology to estimate changes in the mean radiant temperature (T_{MRT}) and related meteorological parameters on the total human heat load with a more reflective surface or a shaded surface, and resultant changes to the simulated heat strain parameters of core and skin temperatures (T_{cr}, $\bar{T}_{sk}$), as well as skin wettedness and cardiac output.

The use of reflective pavement slightly increased the T_{MRT} in the morning hours for all cities and times of the year assessed, which caused higher overall radiant heat loads and thus marginally higher (yet insignificant) T_{cr} and $\bar{T}_{sk}$. Thus, while the reflective pavement causes these potential minor increases in simulated heat strain, the directionality of the difference in heat strain (*i.e.,* making the situation worse) is the opposite of what is expected from a heat mitigation technology. These relationships of higher heat stress with high T_{MRT} loads agree with past literature assessing radiation and physiological response (Otani et al. 2021; Otani and Lee 2022). Concerns are heightened given that elevated skin and core (or overall body) temperatures correlate with lower performance and fatigue (Nybo and Nielsen 2001).

Increasing T_{MRT} exposure demonstrated by this modeling study and other field and modeling studies (Erell et al. 2014; Lai et al. 2019; Schneider et al. 2023a) *discourage* the use of reflective pavement in locations with high pedestrian traffic (on a road or recreational area/playground/court), as well as in highly built-up areas (downtown of large cities) where the sun does not interact directly with the horizontal surface (Schneider et al. 2023a). Therefore, while higher T_{MRT} is a well-known trade-off to reducing the surface/subsurface temperatures with such products, using albedo-based products compromises pedestrian thermal comfort in the daytime (Erell et al. 2014). Thus, cities must use reasonable evidence-backed decision-making regarding where and why an albedo-based reflective coating is installed. Further, results here are based on morning hours, as early as 5:00 am in Sapporo. The negative impact of the higher reflectivity on the radiant heat load increases as the day proceeds (**Table 2**), with a higher difference in T_{MRT} at the latest time of the morning (around 11 am). This difference would increase from sunrise until the incoming solar radiation reached its highest value, exacerbating the adverse impacts on athletes compared to non-reflective surfaces.

Importantly, if sporting organizers are looking to spend time and money on providing the safest route possible given the conditions expected, a strategically planned route that offers ample shade and decent airflow—whether on concrete, asphalt, or reflective pavement—will support the most important declines in heat strain parameters, as estimated in the current paper. Medical sports experts agree upon such shading strategies (Schneider et al. 2023b). The shaded versus sun-exposed results here agree with modeling or measurement studies wherein shade significantly reduces heat strain (Lucas 2016; Ioannou et al. 2021; Otani and Lee 2022; Clark and Konrad 2023; Meng et al. 2023). For example, work completed in Tokyo by Vanos et al. (2019)—prior to organizers moving the marathon and race-walk to Sapporo—showed that the provision of shade throughout the route, based on multi-day microscale mobile measurements of radiation, temperature, and humidity, provided the most relief to spectators along the course. Ample shade can be provided by tall buildings in downtown areas where these events are often held or by other forms of built and natural shade. These high-rise downtown areas are also known to present "urban cool islands" (UCI) in the morning hours before the sun has had a chance to reach the city surfaces due to the blocking of radiation by buildings (Alonso et al. 2003; Basara et al. 2008; Marc et al. 2014; Yang et al. 2017; Hardin et al. 2018). These shading/UCI features and additional air flow/ventilation can support cooler routes for marathoners and racewalkers and enhance performances.

The event's location (city) and time of day or year are critical factors in the expected overall heat strain. The local microclimatic conditions result in differences in estimated heat strain parameters when comparing the reflective pavement or shaded asphalt to traditional open asphalt. These results can give clues as to the best route at the given time of day or other helpful heat mitigation technologies supported by the climate (e.g., mist can be helpful in dry locations versus humid). Overall, the large impact of solar radiation on heat load, even in the morning hours, should be decreased via design, not increased.

The thermoregulation model facilitated a thorough and more specific evaluation of heat strain parameters in athletes, including T_{cr}, $\bar{T}_{sk}$, skin wettedness, and cardiac output across diverse simulated race scenarios. A reduction in core temperature of -0.37°C, on average, from shade, though seemingly modest, can significantly reduce or delay the risk of exertional heat stroke in hot conditions, such as those anticipated for the Los Angeles Olympic and Paralympic Games. Additionally, the resultant lower thermal strain from shade would likely enhance athlete performance and safety (Nybo and Nielsen 2001). The incorporation of solar radiation, and thus T_{MRT}, is often ignored within common thermal indices, yet must be accounted for in outdoor scenarios given the strong relationship with heat stress (Hodder and Parsons 2007; Middel et al. 2016; Foster et al. 2022; Nelson et al. 2024) and cognition (Piil et al. 2020). This interdisciplinary research highlights the intricate factors affecting outdoor potential heat strain in dynamic microclimates, emphasizing a holistic and ethical approach that seeks to minimize the dependence on direct indoor experimentation on human subjects or athletes in evaluating potential mitigation strategies. Insights herein provide organizers with valuable information to adjust schedules based on location, urban design, time of day, and weather conditions, ensuring athlete safety amid extreme heat.

Limitations

Model inputs assumed athletes with specific BMIs representing the average athletes from particular sports groups (based on the literature). The ability to regulate body temperature depends on several factors such as age, underlying medical conditions, hydration, heat acclimation status, etc. (Flouris and Schlader 2015; Romanovsky 2018; Périard et al. 2021; Cramer et al. 2022). The present study used an open-source thermoregulation model validated for outdoor sports (marathon, triathlon, football, tennis, etc.), where heat acclimatization was not implemented. Therefore, we also did not consider the heat acclimatization status of athletes. Further, the thermoregulation model does not account for ethnic differences in thermal physiology and for the effectiveness of other external cooling methods that athletes would use in these hot conditions (e.g., water dousing, ice slurry ingestion, etc.) commonly employed across various sports. Given this is a heat strain simulation study, there is a need to complete empirical research to monitor the physiological heat strain responses and perceptions during races (e.g., (Aylwin et al. 2023)).

Regarding urban microclimate estimations, observed wind speed at human height was used as the main input, rather than relative wind velocity. We assume constant metabolic rates among athletes given that human data were not collected and to isolate the thermal and radiative components on the human body. We acknowledge that athletes' metabolic rates often decrease over the course of a long race, particularly in hot conditions (Noakes et al. 1991; Mantzios et al. 2022), and future work may assess more dynamic modeling to address dynamic sensitivities. Further, we apply a constant windspeed as airflow over the body and do not account for variations in wind speed or effective wind speed (*i.e.*, wind velocity plus moving speed and direction) and its impact evaporative and convective heat transfer. Future studies should aim to incorporate improved convective heat transfer coefficients that account for outdoor wind characteristics, such as turbulence intensity and length scale, due to their significant impact on convection (Joshi et al. 2024). While our model incorporates factors such as clothing insulation and evaporative resistance, it does so under static conditions, not fully capturing the dynamic changes occurring during movement (Joshi et al. 2021). We also did not account for intermittent instances of shade and sun-exposure as these are beyond the scope of the study purpose and we do not have such information for all courses yet.

Conclusion

This study presents a new approach that couples urban microclimate and human thermoregulation modeling to determine the impact of two well-known urban heat mitigation strategies—reflective pavement and shade—on the predicted human heat strain of athletes competing in road events (mainly marathon and 50 km race-walk) in past and future Olympics (Tokyo (Sapporo), Paris, Los Angeles). Reflective pavement slightly increased the average T_{MRT} (1.2–2.2°C), which caused higher overall radiant heat loads and thus slightly higher (yet insignificant) T_{cr} and $\bar{T}_{sk}$. These changes in heat strain (*i.e.,* worsening the situation) are the opposite of what is expected from a heat mitigation technology. Overall, the minor increase in T_{MRT} over reflective pavement transferred a negligible difference in athlete heat strain over a 2–3 hour intense competition. However, shading the athletes results in lower estimated T_{cr} (-0.37°C) and $\bar{T}_{sk}$ (-0.68°C) across the events compared to sun-exposed asphalt, also decreasing cardiac output. Such results point to the importance of accounting for radiant heat load when modeling human heat strain.

Importantly, if sporting organizers and cities are looking to spend time and money on providing a more thermally-acceptable route given the syntoptic conditions expected, a strategically planned route that provides ample shade and decent airflow (which are most modifiable through urban design)—whether on concrete, asphalt, or reflective pavement—will support the most important declines in heat strain parameters. Overall, under warm-hot conditions, the large impact of solar radiation (even in the morning hours of these events) should be decreased via leveraging design strategies that block the sun rather than those that increase radiant heat load. This work, bridging multiple disciplines across physiology, bioclimatology, and urban climate research, can enable or motivate future studies using microclimatic measurements directly linked to heat strain measurements in athletes to further support decision making.

References

Alonso MS, Labajo JL, Fidalgo MR (2003) Characteristics of the urban heat island in the city of Salamanca, Spain. Atmósfera 16:137–148

Arcelli E (1996) Marathon and 50km walk race: physiology, diet and training. New Studies in Athletics 11:51–58

Asaeda T, Ca VT (1993) The subsurface transport of heat and moisture and its effect on the environment: A numerical model. Boundary Layer Meteorol 65:159–179. https://doi.org/10.1007/BF00708822

Aylwin P, Havenith G, Cardinale M, et al (2023) Thermoregulatory responses during road races in hot-humid conditions at the 2019 Athletics World Championships. J Appl Physiol 134:1300–1311. https://doi.org/10.1152/japplphysiol.00348.2022

Basara JB, Hall Jr PK, Schroeder AJ, et al (2008) Diurnal cycle of the Oklahoma City urban heat island. Journal of Geophysical Research: Atmospheres 113:

Bouchama A, Abuyassin B, Lehe C, et al (2022) Classic and exertional heatstroke. Nat Rev Dis Primers 8:1–23

City of Phoenix (2021) City of Phoenix Cool Pavement Pilot Program. https://www.phoenix.gov/streets/coolpavement#:~:text=The%20pilot%20ended%20in%202021,the%20day%20versus%20traditional%20asphalt. Accessed 16 Dec 2023

Clark J, Konrad CE (2023) Observations and Estimates of Wet Bulb Globe Temperature in Varied Microclimates. J Appl Meteorol Climatol

Cramer MN, Gagnon D, Laitano O, Crandall CG (2022) Human Temperature Regulation Under Heat Stress in Health, Disease, and Injury. Physiol Rev 102:1907–1989. https://doi.org/10.1152/PHYSREV.00047.2021

DeMartini JK, Casa DJ, Belval LN, et al (2014) Environmental conditions and the occurrence of exertional heat illnesses and exertional heat stroke at the Falmouth Road Race. J Athl Train 49:478–485

Dunn RJH (2019) HadISD version 3: monthly updates, Hadley Centre Technical NoteDunn, R. J. H., (2019), HadISD version 3: monthly updates, Hadley Centre Technical Note

Dunn RJH, Willett KM, Parker DE, Mitchell L (2016) Expanding HadISD: Quality-controlled, sub-daily station data from 1931. Geoscientific Instrumentation, Methods and Data Systems 5:473–491

Erell E, Pearlmutter D, Boneh D, Kutiel PB (2014) Effect of high-albedo materials on pedestrian heat stress in urban street canyons. Urban Clim 10:367–386. https://doi.org/https://doi.org/10.1016/j.uclim.2013.10.005

Farley GR, Hamley EJ (1978) Progressive changes in energy cost during a three-hour race-walk exercise. Br J Sports Med 12:176

Flouris AD, Babar Z, Ioannou LG, et al (2021) Improving the evidence on health inequities in migrant construction workers preparing for big sporting events. BMJ 374:

Flouris AD, Schlader ZJ (2015) Human behavioral thermoregulation during exercise in the heat. Scand J Med Sci Sports 25:52–64. https://doi.org/10.1111/sms.12349

Foster J, Smallcombe JW, Hodder S, et al (2022) Quantifying the impact of heat on human physical work capacity; part III: the impact of solar radiation varies with air temperature, humidity, and clothing coverage. Int J Biometeorol 66:175–188. https://doi.org/10.1007/s00484-021-02205-x

Georgescu M, Morefield PE, Bierwagen BG, Weaver CP (2014) Urban adaptation can roll back warming of emerging megapolitan regions. Proceedings of the National Academy of Sciences 111:2909–2914

Gomez-Ezeiza J, Tam N, Torres-Unda J, et al (2018) Anthropometric characteristics of top-class Olympic race walkers. J Sports Med Phys Fitness 59:429–433

Grimmond CSB, Cleugh HA, Oke TR (1991) An objective urban heat storage model and its comparison with other schemes. Atmospheric Environment Part B Urban Atmosphere 25:311–326. https://doi.org/https://doi.org/10.1016/0957-1272(91)90003-W

Grundstein A, Vanos J (2020) There is no ‘Swiss Army Knife’ of thermal indices: the importance of considering ‘why?’ and ‘for whom?’ when modelling heat stress in sport. Br J Sports Med bjsports-2020-102920. https://doi.org/10.1136/bjsports-2020-102920

Guo H, Aviv D, Loyola M, et al (2020) On the understanding of the mean radiant temperature within both the indoor and outdoor environment, a critical review. Renewable and Sustainable Energy Reviews 117:109207. https://doi.org/https://doi.org/10.1016/j.rser.2019.06.014

Guzman-Echavarria G, Middel A, Vanos JK (2023) Beyond heat exposure-new methods to quantify and link personal heat exposure, stress, and strain in diverse populations and climates: The journal Temperature Toolbox. Temperature 10:358–378

Hardin AW, Liu Y, Cao G, Vanos JK (2018) Urban heat island intensity and spatial variability by synoptic weather type in the northeast US. Urban Clim 24:747–762. https://doi.org/10.1016/j.uclim.2017.09.001

Harris JA, Benedict FG (1918) A biometric study of human basal metabolism. Proceedings of the National Academy of Sciences 4:370–373

Havenith G (2001) Individualized model of human thermoregulation for the simulation of heat stress response. J Appl Physiol 90:1943–1954

Hodder SG, Parsons KC (2007) The effects of solar radiation on thermal comfort. Int J Biometeorol 51:233–250

Honjo T, Seo Y, Yamasaki Y, et al (2018) Thermal comfort along the marathon course of the 2020 Tokyo Olympics. Int J Biometeorol 62:1407–1419

Hosokawa Y, Vanos JK (2020) Extreme heat & health at Tokyo2020ne: The need for scientific coalition across sectors. Temperature

Ioannou LG, Tsoutsoubi L, Mantzios K, et al (2021) The impacts of sun exposure on worker physiology and cognition: multi-country evidence and interventions. Int J Environ Res Public Health 18:7698

ISO9920 (2007) ISO 9920: Ergonomics of the Thermal Environment: Estimation of thermal insulation and water vapour resistance of a clothing ensemble. ISO, Geneva

Jacobson MZ (2005) Fundamentals of Atmospheric Modeling, Cambridge University Press, Cambridge. UK

Japanese Government (2022) Overview of Heat-Reflective Pavement.

Japanese Government (2016) The Proposal for Creating Athlete- and Audience-Friendly Environments.

Jia X, Li S, Zhu Y, et al (2023) Transient thermal comfort and physiological responses following a step change in activity status under summer indoor environments. Energy Build 285:112918

Johansson E, Emmanuel R (2006) The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. Int J Biometeorol 51:119–133

Joshi A, Psikuta A, Bueno M-A, et al (2021) Effect of movement on convection and ventilation in a skin-clothing-environment system. International Journal of Thermal Sciences 166:106965

Joshi A, Viswanathan SH, Jaiswal AK, et al (2024) Characterization of human extreme heat exposure using an outdoor thermal manikin. Science of The Total Environment 171525

Joshi A, Wang F, Kang Z, et al (2022) A three-dimensional thermoregulatory model for predicting human thermophysiological responses in various thermal environments. Build Environ 207:108506

Kántor N, Chen L, Gál C V (2018) Human-biometeorological significance of shading in urban public spaces—Summertime measurements in Pécs, Hungary. Landsc Urban Plan 170:241–255

Kosaka E, Iida A, Vanos J, et al (2018) Microclimate variation and estimated heat stress of runners in the 2020 Tokyo Olympic Marathon. Atmosphere (Basel) 9:. https://doi.org/10.3390/atmos9050192

Kousis I, Pisello AL (2023) Evaluating the performance of cool pavements for urban heat island mitigation under realistic conditions: A systematic review and meta-analysis. Urban Clim 49:101470. https://doi.org/https://doi.org/10.1016/j.uclim.2023.101470

Krayenhoff ES, Moustaoui M, Broadbent AM, et al (2018) Diurnal interaction between urban expansion, climate change and adaptation in US cities. Nat Clim Chang 8:1097–1103

Lai D, Liu W, Gan T, et al (2019) A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. Science of The Total Environment 661:337–353. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.01.062

Lindberg F, Holmer B, Thorsson S (2008) SOLWEIG 1.0 - Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. Int J Biometeorol 52:697–713. https://doi.org/10.1007/s00484-008-0162-7

Lucas R (2016) Intervention to reduce heat stress and improveefficiency among sugarcane workers in El Salvador–Phase. Occup Environ Med

Makaremi N, Salleh E, Jaafar MZ, GhaffarianHoseini A (2012) Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia. Build Environ 48:7–14

Malek MH, Berger DE, Housh TJ, et al (2004) Validity of VO2max equations for aerobically trained males and females. Med Sci Sports Exerc 36:1427–1432

Mantzios K, Ioannou LG, Panagiotaki Z, et al (2022) Effects of weather parameters on endurance running performance: Discipline-specific analysis of 1258 races. Med Sci Sports Exerc 54:153

Marc A, Sedeaud A, Guillaume M, et al (2014) Marathon progress: demography, morphology and environment. J Sports Sci 32:524–532

Meng Y, Wang J, Xi C, et al (2023) Investigation of heat stress on urban roadways for commuting children and mitigation strategies from the perspective of urban design. Urban Clim 101564

Middel A, AlKhaled S, Schneider FA, et al (2021) 50 grades of shade. Bull Am Meteorol Soc 102:E1805–E1820

Middel A, Selover N, Hagen B, Chhetri N (2016) Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. Int J Biometeorol 60:1849–1861. https://doi.org/10.1007/s00484-016-1172-5

Middel A, Turner VK, Schneider FA, et al (2020) Solar reflective pavements—A policy panacea to heat mitigation? Environmental Research Letters 15:64016

Nelson J, Vanos J, Havenith G, et al (2024) Global reductions in manual agricultural work capacity due to climate change. Glob Chang Biol. https://doi.org/10.1111/gcb.17142

Noakes TD, Myburgh KH, Du Plessis J, et al (1991) Metabolic rate, not percent dehydration, predicts rectal temperature in marathon runners. Med Sci Sports Exerc 23:443–449

Nybo L, Nielsen B (2001) Hyperthermia and central fatigue during prolonged exercise in humans. J Appl Physiol 91:1055–1060
Oke TR, Mills G, Christen A, Voogt JA (2017) Urban Climates, 1st edn. Cambridge University Press, Cambridge
Otani H, Kaya M, Tamaki A, et al (2019) Exposure to high solar radiation reduces self-regulated exercise intensity in the heat outdoors. Physiol Behav 199:191–199
Otani H, Kaya M, Tamaki A, et al (2021) Combined effects of solar radiation and airflow on endurance exercise capacity in the heat. Physiol Behav 229:113264
Otani H, Kaya M, Tsujita J (2013) Effect of the volume of fluid ingested on urine concentrating ability during prolonged heavy exercise in a hot environment. J Sports Sci Med 12:197
Otani H, Lee JKW (2022) The use of sun-shade on safe heat exposure limit on a sunny summer day: a modelling study in Japan. Int J Biometeorol 66:731–740
Oyama T, Fujii M, Nakajima K, et al (2023) Validation of upper thermal thresholds for outdoor sports using thermal physiology modelling. Temperature 1–15
Périard JD, Eijsvogels TMH, Daanen HAM (2021) Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. Physiol Rev
Piil JF, Christiansen L, Morris NB, et al (2020) Direct exposure of the head to solar heat radiation impairs motor-cognitive performance. Sci Rep 10:1–10. https://doi.org/10.1038/s41598-020-64768-w
Racinais S, Ihsan M, Taylor L, et al (2021) Hydration and cooling in elite athletes: relationship with performance, body mass loss and body temperatures during the Doha 2019 IAAF World Athletics Championships. Br J Sports Med 55:1335–1341
Rida M, Abdelfattah M, Alahi A, Khovalyg D (2023a) Toward contactless human thermal monitoring: A framework for Machine Learning-based human thermo-physiology modeling augmented with computer vision. Build Environ 245:110850
Rida M, Frijns A, Khovalyg D (2023b) Modeling local thermal responses of individuals: Validation of advanced human thermo-physiology models. Build Environ 243:110667
Romanovsky AA (2018) The thermoregulation system and how it works, 1st edn. Elsevier B.V.
Roza AM, Shizgal HM (1984) The Harris Benedict equation reevaluated: resting energy requirements and the body cell mass. Am J Clin Nutr 40:168–182
Schneider FA, Ortiz JC, Vanos JK, et al (2023a) Evidence-based guidance on reflective pavement for urban heat mitigation in Arizona. Nat Commun 14:1467. https://doi.org/10.1038/s41467-023-36972-5
Schneider S, Niederberger M, Kurowski L, Bade L (2023b) How can outdoor sports protect themselves against climate change-related health risks? – A prevention model based on an expert Delphi study. J Sci Med Sport. https://doi.org/https://doi.org/10.1016/j.jsams.2023.11.002
Sengupta M, Xie Y, Lopez A, et al (2018) The National Solar Radiation Data Base (NSRDB). Renewable and Sustainable Energy Reviews 89:51–60. https://doi.org/10.1016/j.rser.2018.03.003
Stull RB (2015) Practical meteorology: an algebra-based survey of atmospheric science. University of British Columbia
Takahashi Y, Nomoto A, Yoda S, et al (2021) Thermoregulation model JOS-3 with new open source code. Energy Build 231:110575

Thorsson S, Rayner D, Palm G, et al (2020) Is Physiological Equivalent Temperature (PET) a superior screening tool for heat stress risk than Wet-Bulb Globe Temperature (WBGT) index? Eight years of data from the Gothenburg half marathon. Br J Sports Med

Tokyo Shimbun (2023) What Happened to Tokyo Olympics' Heat Mitigation Pavement? Tokyo Continues Maintenance, but the National Effort... What About Morning Glories and Water Splashing. Tokyo Shimbun

Turner VK, Middel A, Vanos JK (2023) Shade is an essential solution for hotter cities. Nature 619:694–697

Vanos JK, Herdt AJ, Lochbaum MR (2017) Effects of physical activity and shade on the heat balance and thermal perceptions of children in a playground microclimate. Build Environ 126:. https://doi.org/10.1016/j.buildenv.2017.09.026

Vanos JK, Kosaka E, Iida A, et al (2019) Planning for spectator thermal comfort and health in the face of extreme heat: The Tokyo 2020 Olympic marathons. Science of the Total Environment 657:. https://doi.org/10.1016/j.scitotenv.2018.11.447

Vanos JK, Rykaczewski K, Middel A, et al (2021) Improved methods for estimating mean radiant temperature in hot and sunny outdoor settings. Int J Biometeorol 65:967–983

Vargas NT, Chapman CL, Ji W, et al (2020) Increased skin wetness independently augments cool-seeking behaviour during passive heat stress. J Physiol 598:2775–2790. https://doi.org/10.1113/JP279537

Xu X, Rioux TP, Castellani MP (2023) Three dimensional models of human thermoregulation: A review. J Therm Biol 103491

Yang X, Li Y, Luo Z, Chan PW (2017) The urban cool island phenomenon in a high-rise high-density city and its mechanisms. International Journal of Climatology 37:890–904

Zhang Q, Ding L, Xu R, et al (2023) Human thermoregulatory model for simulating thermal response in high-temperature and hypobaric environments. Case Studies in Thermal Engineering 52:103682