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# Correlation Between Estimated Thermoregulatory Responses and Pacing in Athletes During Marathon

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**ABSTRACT** Performance and completion rates in marathons attract considerable attention in race planning and risk management. Previous studies have explored the relationship between several parameters, including athlete age and weather, and marathon performance. In this study, for the first time, we correlate the computational estimation of core body temperature and perspiration of athletes with speed loss and completion rate in marathon races. A feature of this method is that nonlinear thermo-physiological responses, that is, core temperature change and sweating, are followed in the time domain for ambient conditions. Our computational estimation was in good agreement with group-level core temperature rise and perspiration in typical marathon races. When the ambient conditions in previous World Athletics Championships and Olympic Games were replicated, the estimated perspiration was better correlated with the marathon speed ($R^2 = 0.50$, $p < 0.05$ in men) than with the ambient temperature ($R^2 = 0.37$, not statistically significant), which was used in conventional studies. The correlation for female athletes was better than that for male athletes. A weak correlation was observed between the completion rate and ambient conditions, as well as the thermo-physiological response in male athletes ($R^2 = 0.3$), whereas a strong correlation was observed in female athletes ($R^2 = 0.7$). This method was applied to estimate pacing in the upcoming Olympic Games in 2021 to discuss the effect of location change on marathon performance. The findings of this study may be useful for race pacing and risk management of heat-induced illness.

**INDEX TERMS** Thermoregulation, marathon pacing, core temperature, perspiration, prediction of performance.

## I. INTRODUCTION

In homeotherms, body temperature is maintained within a narrow range depending on the balance of dissipation and retention of metabolic heat. If the core temperature increases due to exercise and environmental heat, sweat is produced to cool the body temperature via the evaporative heat loss process. However, intense and prolonged exercise may cause significant hypohydration and temperature rise, resulting in dehydration and hyperthermia. These can eventually impair performance and become a factor that limits exercise performance [1], [2].

Owing to the scheduling compatibility, the Summer Olympic Games and the World Athletics Championships (WAC) are held in summer, typically from July to August. Changing the schedules of major sports events because of weather is virtually impossible because they are decided several years in advance. Hence, it is essential to effectively manage risk to athletes that are attributable to environmental heat. Among other sports, the health management of marathon athletes is a major concern [3].

The performance of marathon athletes in different environments is an ongoing topic of discussion (e.g., [4]–[7]), and the completion rate of a race is another concern. In WAC 2019, which was held in Doha, the completion rate in the women's race was only 60%. At the beginning of the race

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day, the ambient temperature and relative humidity (RH) were 33 °C and 73%, respectively. This low completion rate may be attributed to environmental heat or related to exertional heat stroke [8]. Similar to the Doha race, substantial attention was paid to acclimation to the environment in Tokyo 2021 [9], [10]. In November 2019, the International Olympic Committee decided to change the location of the marathon for the 2021 Olympic Games (Tokyo, Japan) to Sapporo, which is located on the northern island of Japan and has a milder climate than Tokyo. However, the impact of this location change on athlete performance is unclear. Meanwhile, the schedule of the Olympic Games is still subject to change because of the COVID-19 crisis.

The relationship of marathon time with ambient conditions and physiological parameters has attracted considerable attention for improving athlete performance [6], [11]–[16]. In [11], the core temperature rise of athletes was measured in which the core temperature reached a steady state after 35–45 min (39 °C and 40 °C for two athletes). In the last 44 min, the core temperature reached 41 °C, although the skin temperature was 24 °C. The post-race rectal temperature was 38.3 ± 0.9 °C for the 1982 Aberdeen Marathon race (ambient temperature of 12 °C). For different athletes, the correlation between the post-race rectal temperature and finishing time was not statistically significant [12]. In [13], the core body temperature and water intake were measured in a 21-km road race. The main findings of the study were as follows: i) running velocity was a significant predictor variable of core body temperature, and ii) hyperthermia, which is characterized by the deep body temperature being greater than 39.5 °C, was common in trained individuals who undertook outdoor distance running in environmental heat, without any evidence of fatigue or heat-related illness. However, the number of subjects was limited and the timing of their recording was generally at the end of the race [17], or the number of parameters recorded by sensors was limited (e.g., heart rate variability [18]). A straightforward comparison of these studies is difficult because of the variability of athletes (general population versus elite athletes) as well as different ambient conditions. Rather, several statistical studies have presented the association of marathon performance with ambient conditions (e.g., air temperature and humidity) (see Section II).

Therefore, it is essential to effectively manage the heat-related risk and performance decrement of athletes. However, conventional studies are based on the statistics of limited measured data. Recently, different information technologies have been reported to improve and estimate marathon pacing and performance: core temperature estimation for health management [19], positioning of athletes [20], monitoring of athletes with wearable devices [21]–[23], performance estimation based on physiological computation, etc. [24]. The approaches with numerical models and devices can be helpful to control pacing and improve the completion rate. If thermo-physiological responses, which are nonlinear and closely related to hyperthermia but cannot be directly measured, are correlated with race performance as well as the risk of athletes, it is useful to determine the marathon location and the risk management of athletes.

In our previous study [25], the number of citizens transported by ambulance in their daily lives was well estimated using computed perspiration and core temperature rise, which comprised the thermo-physiological response to heat stress. The study employed a computational technique that integrates electromagnetics, thermodynamics, and thermo-physiological responses in an anatomical human body model [26], [27]. The computational code was validated by comparison with the measured data in various thermal scenarios, such as resting in variable ambient conditions [27], walking for 30 min, and exercising for 60 min [28].

The estimation of marathon speed loss and completion rate with computationally estimated thermo-physiological responses rather than ambient parameters is a topic to be explored. Otherwise, discussions on the usefulness of conventional ambient parameters are necessary for their estimation. If the applicability of state-of-the-art computational methods, which are often used in the fields of environmental electromagnetic safety and thermal comfort [29]–[31], can be demonstrated for marathon runners (including the general population and elite athletes), it may be used for marathon planning.

In this study, the relationship between marathon pacing and estimated thermo-physiological responses (core temperature rise and total sweating during a race) is demonstrated by simulating the ambient conditions in major races as a pilot study. We also discuss the completion rate using the estimated parameters. The novelty of this article is that computationally estimated thermoregulatory response is introduced for correlation with marathon performance. The main contributions of this study are summarized as follows:

- To demonstrate the applicability of the integrated computational modeling of multiphysics and thermo-physiological response for estimating core temperature and sweating at the group level.
- To establish the relationship between marathon pacing and estimated thermo-physiological responses rather than conventional ambient parameters.
- To estimate the relationship between completion rate with ambient conditions and thermo-physiological responses for planning heat-induced illness during marathons.
- To apply a computational approach to estimate the impact of location (weather) change on the performance of athletes.

This article is organized as follows: In Section II, studies on marathon performance are reviewed. In Section III, a computational human model and a method for estimating the time-course core temperature and perspiration are described, as well as the details of scenarios simulated in this article. In Sections IV and V, the estimated thermo-physiological response with the measured data during the race is first validated. The relationship between race speed

**TABLE 1.** Related Studies which discussed the effect of ambient parameters on marathon performance.

| | Performance | Factors | Marathon race | Gender | Years |
|---|---|---|---|---|---|
| Ely et al. [5] | 5 km times and finishing time | Ambient temperature | Women's championship marathons in Japan (Tokyo, Osaka, and Nagoya) | Female | 1982-2007 |
| Helou et al. [6] | Speed loss | Ambient temperature, relative humidity, dew point, atmospheric pressure, and atmospheric pollutants | European and American marathon | Male/Female | 2001-2010 |
| Gasparetto and Nesseler [33] | Running speed | WBGT, UTCI | New York City Marathons | Male/Female | 2006-2018 |
| Knechtle et al. [35] | Race time | Average ambient temperature, precipitations, WBGT, wind speed/direction, and barometric pressure | Boston Marathon | Male | 1972-2018 |
| Cheuvront and Haymes [1] | Running speed | Rectal temperature and dehydration (estimated from simple liner regression) | Related 19 papers | Male (limited to statistical estimation of thermoregulation) | Review paper |

and thermo-physiological response is then demonstrated. Furthermore, these relationships are extended to explain the completion rate. Finally, the findings of this study are summarized in Section VI.

## II. RELATED STUDIES AND MOTIVATION

Related studies on the effect of ambient parameters on marathon performance summarized in Table 1. Ely *et al.* [5] and Helou *et al.* [6] reported the correlation between ambient temperature and race speed. In [5], the records of the 1st, 25th, 50th, and 100th place finishers in 62 female marathon races were analyzed using a mixed-model ANOVA. The warmer ambient temperature decreased the speed of the 1st and 25th place finishers, but this tendency was not observed in other finishers. A difference in average race speed of last 5-km split times was statistically significant with ambient temperature. In [6], the effect of ambient conditions on marathon speed was statistically evaluated for 1,791,972 athletes in six major competitions (Berlin, Boston, Chicago, London, New York, and Paris from 2001 to 2010). One main finding of the study was that the ambient temperature was a dominant factor in determining speed loss. In addition, if most athletes dropped out of the races because of heat-related illness, other factors, such as RH and wind speed, would not be negligible.

Meanwhile, the effect of wet-bulb globe temperature (WBGT) on pacing has also been discussed [14], [32]. Montain *et al.* [14] reported that the marathon pacing declined with increasing WBGT above a certain level. In addition, the optimal temperatures for the best speed of runners are different owing to the running performance level. Gasparetto and Nesseler [33] analyzed the performances of runners using the WBGT and universal thermal climate index (UTCI), which is an index with a slightly different measure of thermal perception based on air temperature and humidity. Note that WBGT considers RH, wind speed, and visible and infrared radiations; thus, it may be considered as a heat load on the body [34].

Knechtle *et al.* [35] investigated the relationship between marathon performance and weather conditions. The main findings were that higher ambient temperatures led to a decrease in the marathon performance. Cheuvront and Haymes [1] reported that the running speed was significantly correlated with rectal temperature, which was statistically estimated from linear regression analysis.

## III. METHODS

### A. ANATOMICAL HUMAN MODELS

Japanese male and female models were used as references in this study [36]. The height and weight of the male model were 1.73 m and 65 kg, respectively, while those of the female model were 1.60 m and 53 kg, respectively. The estimated surface areas of the male and female models were 1.78 and 1.54 m$^2$, respectively [37] Figure 1 illustrates the anatomical human model and defines the body parts for computing blood temperature. The body-part model is considered to approximately represent a compartment model (e.g., cylinders in [38], [39]), which is often utilized for a simpler computation.

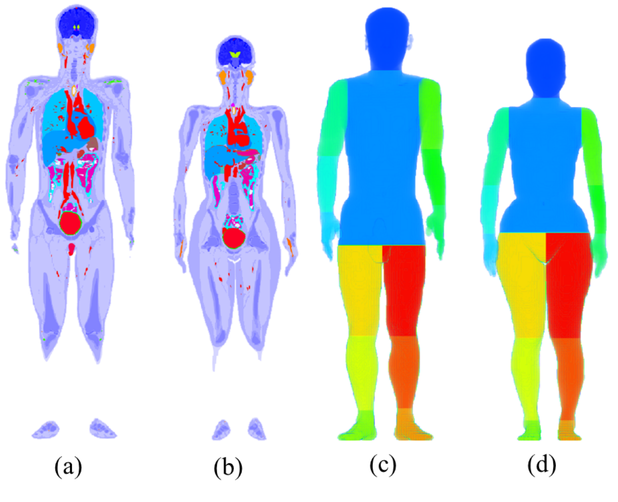

**FIGURE 1.** Cross-section of three-dimensional anatomical human adult (a) male and (b) female model; (c, d) definition of body parts for computing blood temperature.

## B. THERMAL ANALYSIS

A detailed explanation of our in-house computational code was reported in our previous study [26], [27]. In addition to ambient temperature, humidity, and (average) wind velocity, the heat generated by solar and infrared radiations can be considered. The thermoregulation of the human models was based on an adult (general population) who lived in a temperate zone [28], [40].

### 1) BIOHEAT EQUATION

The temperature in the human model follows a finite-difference time domain for Pennes' bioheat transfer equation [41]. A generalized form of this equation is given as:

$$\begin{aligned} C(r)\rho(r)&\frac{\partial T(r,t)}{\partial t} \\ &= \nabla\left(K(r)\nabla T(r,t)\right)+\sigma(r)E^2(r,t) \\ &\quad +M(r,t)-B(r,t)\left(T(r,t)-T_B(t)\right), \end{aligned} \tag{1}$$

where $T$ denotes the tissue temperature at position $r$ and time $t$; $T_B$ denotes the blood temperature of each body part ($m = 1, \ldots, 13$, where $m$ represents the body parts shown in Fig. 1(b)); $C$ denotes the specific heat of the tissue; $\rho$ denotes the tissue density; $K$ denotes the thermal conductivity of the tissue; $M$ denotes the metabolic heat generation, including the heat load of the marathon; $E$ denotes the internal electric field caused by solar radiation; and $B$ denotes a term associated with blood perfusion and varies according to temperature change [31]. Metabolic heat generation includes basal metabolism and heat generation from exercise. The metabolic heat generation is assumed to be uniformly distributed on the muscle tissues over the body and is a constant. Although the metabolic rate is assumed to be constant over time, a realistic simulation can be considered with measured data [42].

The boundary condition between air and tissue for (1) is given as:

$$-K(\mathbf{r})\frac{\partial T(\mathbf{r},t)}{\partial n} = H(\mathbf{r})\cdot\left(T(\mathbf{r},t)-T_a(t)\right)+EV(\mathbf{r},t) \tag{2}$$

where $H$, $T_a$, and $EV$ denote the heat transfer coefficient, ambient temperature, and evaporative heat loss, respectively. The heat transfer coefficient includes convective and radiative heat losses, along with estimated wind speed based on the measurement [39].

The initial temperature distribution in a thermoneutral condition was computed by (1) and (2) using the naked human at the ambient temperature $T_a = 30$ °C, at which the thermoregulation measures, such as blood perfusion, sweating, and blood temperature, remained constant.

The blood temperature was modeled according to [40], in which arterial and venous temperatures were separately considered [28]. In this study, we define arterial blood temperature in the head and trunk as the core temperature.

### 2) MODELING OF THERMOREGULATORY RESPONSE

The blood perfusion rate via vasodilatation was changed in the same manner as in [31]. The evaporative heat loss from the skin is given as:

$$\begin{aligned} EV &= \min\left\{SW(r,t)\cdot 40.6/S,\ EV_{\max}\right\}, \\ EV_{\max} &= 2.2\cdot h_c f_{pcl}\left(P_S-\varphi_\varepsilon P_A\right), \\ h_c &= 3.0\sqrt{10v}, \end{aligned} \tag{3}$$

where $SW$ is the sweating rate (refer to (4)), $S$ is the total surface area of the human body, and 40.6 is the conversion coefficient. The maximum evaporative heat loss, $EV_{max}$, from the skin depends on the ambient conditions. $h_c$ is the convective heat transfer coefficient approximated in [38]; $v$ is the wind velocity; $P_S$ and $P_A$ are the saturated water vapor pressures at skin and ambient air temperatures, respectively; $\varphi_e$ is the RH of ambient air; and $f_{pcl}$ is the permeation efficiency factor of clothing, which depends on air movement speed. For simplicity, $f_{pcl}$ was assumed to be 0.7 for body parts with clothing and 1 for most limbs that are not covered by clothing and shoes [43], [44].

The $SW$ was assumed to depend on the temperature rises of the skin and the hypothalamus according to the following equation [40]:

$$\begin{aligned} SW(r,t) &= \gamma(r)\cdot\chi(r)\left(W_S(t)\Delta T_S(t)+W_H(t)\Delta T_H(t)\right)+PI, \\ W_S(t) &= \alpha_{11}\tanh\left(\beta_{11}T_S(t)-\beta_{10}\right)+\alpha_{10}, \\ W_H(t) &= \alpha_{21}\tanh\left(\beta_{21}T_H(t)-\beta_{20}\right)+\alpha_{20}, \end{aligned} \tag{4}$$

where $\Delta T_S$ and $\Delta T_H$ are the temperature rises of the skin (averaged over the body) and hypothalamus, respectively. The insensible water loss, $PI$, which is 0.71 and 0.58 g/min for men and women, respectively, is based on weight and height [28], [27]. The multiplier $\gamma$(r) denotes the dependence of $SW$ on the body parts [40]. The coefficients $\alpha$ and $\beta$ are estimated for an average $SW$ based on the measurements derived in [45].

The SX-ACE supercomputer used for the computation is a vector-type computer with a high vector processing performance of 256 GFLOPS per CPU and a high memory bandwidth of 256 GB/s [46]. No adjustment of the parameters of the thermal constant of tissues in (2) and nonlinear thermo-physiological response in (4) has been made from our previous studies [27], [28], in which validation has been done for resting, walking, and exercising in various ambient conditions.

## C. SCENARIOS

The athlete is assumed to wear a sleeveless shirt and shorts. Ambient temperatures lower than temperatures that provide heat balance may be related to shivering and vasoconstriction. However, we are interested in high ambient temperature because the speed loss and completion rate are significant. As this effect is beyond the scope of this study, ambient temperatures higher than 7 °C were considered in this study. Note that this temperature is a threshold where the performance (race speed) becomes maximum [6].

In this study, a constant metabolic rate of 13.3 METs was assumed during the running period [47]. The solar radiation (electromagnetic power absorption) was adjusted in a way similar to [42], based on the global solar radiation in each scenario. In the course of a marathon race, the angle of solar radiation changes with time and location. However, this information was not available and was therefore simplified to apply a mean value (refer to the subsequent text).

We then considered the following five scenarios to explore the applicability of the computed results to the estimation of speed loss and completion rate in a marathon. The rationale for choosing these scenarios is as follows: The first and second scenarios were used to validate the computational code during the marathon. A computational model for thermoregulation has been developed for the general population. The first purpose of this study is to validate this model for the general population. In addition, its applicability or extension to top-level athletes was explored, although exact data were not available. In the first scenario, athletes at the top level were included. In the second scenario, the participants were not athletes, although they were well trained. The third and fourth scenarios were used to clarify the correlation between thermoregulation and speed loss as well as the association of thermoregulation with marathon speed and completion rate. The fifth scenario was used to estimate the impact of marathon venues or weather data on speed and completion rate. The scenarios are detailed as follows:

1) The first scenario follows the ambient conditions in the 1983 Aberdeen Marathon (42.195 km) [12]. The ambient temperature was 10.8 °C (80% RH) with a wind speed of 7.7 m/s at 11:00. The temperature gradually increased with time and was 11.5 °C (72% RH) with a wind speed of 6.2 m/s at 15:30. The number of male subjects was 59, with a mean height of 1.76 m (standard deviation (SD) of 0.06 m) and mean weight of 70.9 kg (SD of 9.0 kg), including professional and general competitors.
2) The second scenario follows the conditions of a 21-km road race [13]. The mean dry-bulb and wet-bulb temperatures were 26.4 °C and 23.9 °C, respectively, with a wind speed of 2.8 m/s. The starting time was 5:45. These values were approximately considered as the ambient temperature of 26.4 °C and RH of 81%. The number of male subjects was 31, with a mean height of 1.72 m (SD of 0.05 m) and a mean weight of 65.9 kg (SD of 6.1 kg). Twenty-nine subjects were professional soldiers, and the remaining two volunteers were recruited from local running clubs.
3) Sixty scenarios were considered for six major marathons (Berlin, Boston, Chicago, London, New York, and Paris) from 2001 to 2010, as discussed in [6]. The results of the six marathon races for 10 years were statistically analyzed using the performances of 1,791,972 participants. For each condition (six races for 10 years), the thermo-physiological response was computed, assuming a constant metabolic rate of 13.3 METs. The data obtained in these scenarios were used to analyze the relationship of speed loss with the computed core temperature rise and sweating during the marathons.
4) The fourth scenario was used to compute the thermo-physiological response in a realistic environment. We estimated the core temperature rise and perspiration in WAC from 1997 to 2019 [48]. The ambient temperature and RH were obtained from the National Oceanic and Atmospheric Administration's National Data Center Climate Data Online (NNDC CDO) [49].
5) In the fifth scenario, the performance was simulated at the highest and mean ambient conditions in Tokyo and Sapporo from August 6 to 12 in the past 10 years. The simulation was performed to quantify the potential core temperature rise in the 2021 Olympic Games. The mean and worst-case ambient conditions are listed in Table 2.

**TABLE 2. Mean and worst-case ambient conditions in Tokyo and Sapporo from 6–12th August, 2010–2019: (a) Tokyo and (b) Sapporo.**

(A)

| JST | Ambient temperature (°C) | | Relative humidity (%) | | Solar radiation (MJ/m$^2$) | |
|---|---|---|---|---|---|---|
| | Mean | Worst | Mean | Worst | Mean | Worst |
| 6:00 | 26.6 | 31.1 | 81.5 | 75 | 0.11 | 0.12 |
| 7:00 | 29.3 | 31.5 | 78.6 | 73 | 0.50 | 0.63 |
| 8:00 | 28.2 | 32.5 | 75.1 | 70 | 0.96 | 1.2 |
| 9:00 | 29.0 | 33.5 | 71.1 | 68 | 1.41 | 1.9 |

(B)

| JST | Ambient temperature (°C) | | Relative humidity (%) | | Solar radiation (MJ/m$^2$) | |
|---|---|---|---|---|---|---|
| | Mean | Worst | Mean | Worst | Mean | Worst |
| 6:00 | 22.5 | 28.4 | 79.6 | 53 | 0.55 | 0.77 |
| 7:00 | 23.4 | 29.3 | 76.2 | 52 | 0.98 | 1.44 |
| 8:00 | 24.3 | 30.6 | 72.9 | 47 | 1.31 | 1.78 |
| 9:00 | 25.1 | 32.9 | 69.3 | 41 | 1.69 | 2.77 |

## IV. RESULTS

### A. VALIDATION OF COMPUTATIONAL CODE

The first scenario was replicated, as reported in [12]. The computed core temperature rise and sweating rate are shown in Fig. 2. The running duration was 221 ± 37 min. The measured core temperature was 38.3 ± 0.9 °C, and the water loss was 2.02 ± 0.72 kg. The computed results for core temperature and water loss were 38.4 °C and 1.53 kg, respectively. Note that the water loss is defined as the difference between the total amount of sweating and the total amount of water intake (estimated as 1.4 kg, assuming that all subjects drink all the drinking water; applicable only in this discussion).

The second scenario, reported in [13], was replicated. The computed core temperature rise and sweating rate are shown in Fig. 2. The running duration was 107 ± 9 min. The measured core temperature was 39.8 ± 0.5 °C, and the water loss was 2.22 ± 0.61 kg. Meanwhile, the computed results for

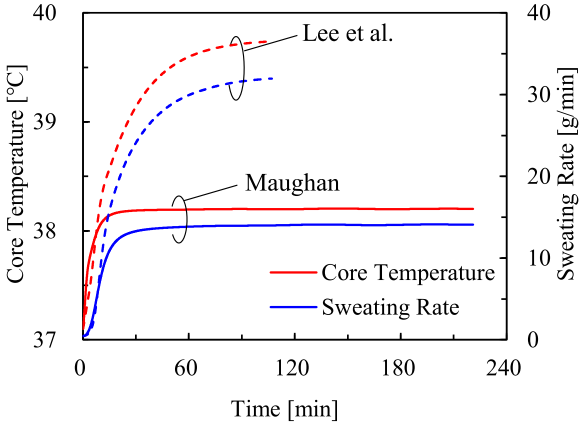

**FIGURE 2.** Time course of core temperature and sweating rate in adult male. Replication of ambient condition was reported by Maughan [12] and Lee *et al.* [13].

the core temperature and water loss were 39.8 °C and 2.31 kg, respectively (considering a water intake of 388 g).

### B. CORE TEMPERATURE RISE AND RATE FOR DIFFERENT CONDITIONS

Fig. 3 shows the heat load balance at an ambient temperature of 25 °C and RH of 50%, in which an increase in skin and core temperatures resulted in sweating, thereby leading to evaporative heating. Owing to vasodilatation, the heat transfer from skin and air marginally increased because of the increase in skin temperature. The heat production exceeded the heat loss, which caused an imbalance of heat load. The evaporation rate, which is defined as the percentage of sweating that can be evaporated, was then evaluated for different ambient conditions.

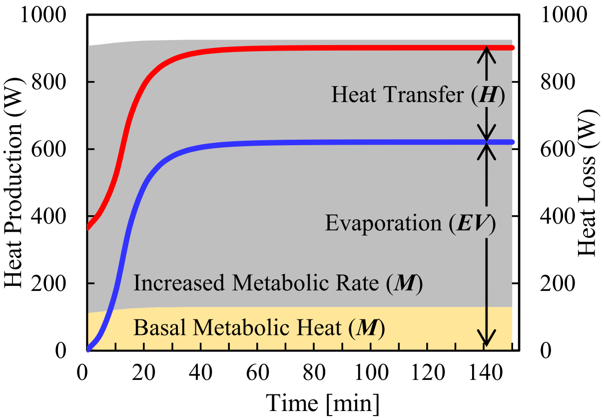

**FIGURE 3.** Heat load balance at 25 °C and 50% RH. Stacked area and line chart represent heat production and loss, respectively.

Fig. 4 shows the associations of the evaporation rate with ambient temperature and wind velocity. The permeation efficiency factor of clothing was assumed to be 0.7. With an increase in ambient temperature or a decrease in wind velocity, the RH threshold became small. The evaporation rate decreased to more than 40% RH at 30 °C, and the heat loss from evaporative cooling became small compared to that from naked. For typical marathon conditions discussed in this study, evaporative cooling is effective. In addition, the effect of air velocity is one of the uncertainty factors.

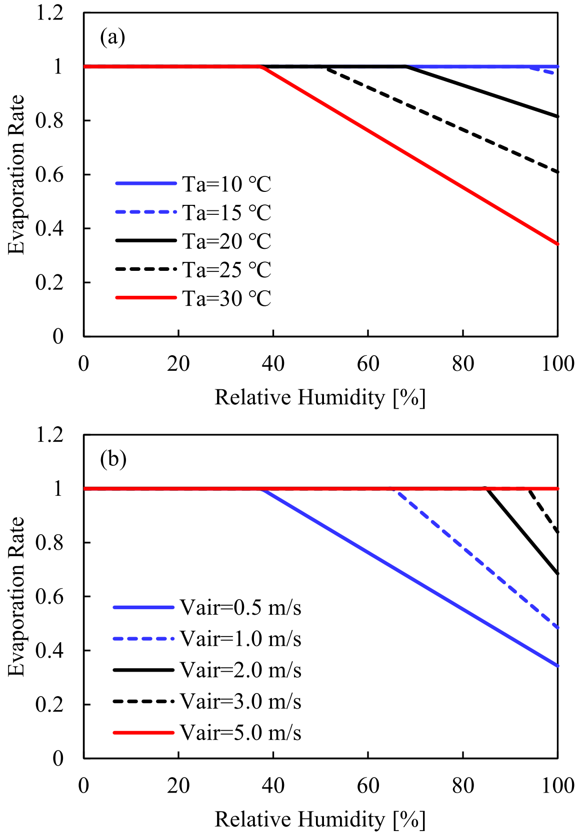

**FIGURE 4.** Associations of evaporation rate with RH for different (a) ambient temperatures and (b) wind velocities. In (a), wind velocity is assumed to be 0.5 m/s, and in (b), ambient temperature is assumed to be 30 °C.

Figs. 5(a) and (b) show the core temperature rise and sweating rate for different ambient temperatures. As shown in the figures, both core temperature rise and sweating rate increased at higher ambient temperatures. For simplicity of discussion, RH can be assumed to be 50% based on Fig. 4 (a). For typical race conditions, the ambient temperature is below 30 °C; thus, the potential difference in the evaporative rate caused by this assumption is less than 10%. As shown in Figs. 5(c) and (d), the impact of metabolic rate, which corresponds to speed, is similar to that of the ambient temperature. An increase in metabolic rate or speed leads to an increase in core temperature rise and sweating rate.

### C. SIX MARATHON RACES FROM 2001 to 2010

In the third scenario for the data reported in [6] (mean value), in which the data of 1,791,972 participants in six marathon races were analyzed, we examined the relationship between ambient temperature and speed loss for the top 1% and bottom 25% athletes. Note that athletes from the general population were considered for the latter.

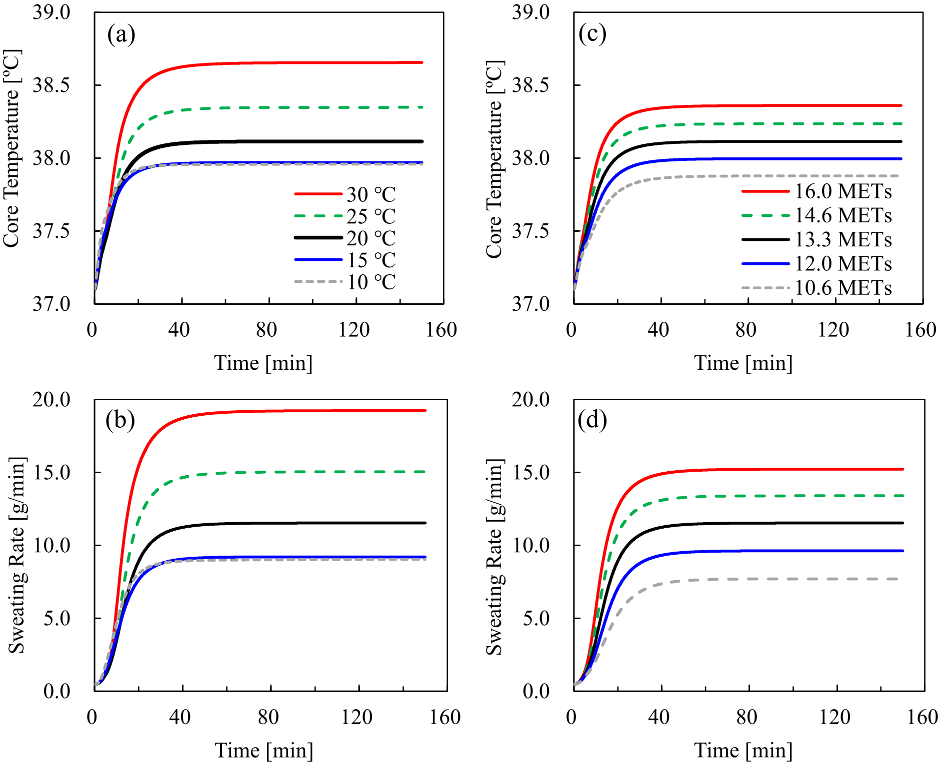

**FIGURE 5.** Time course of core temperature ((a) and (c)) and sweating rates ((b) and (d)) for different ambient temperatures and metabolic rates of male subject. In (a) and (b), The heat load due to exercise was assumed to be 13.3 METs. In (c) and (d), an ambient temperature of 20 °C was assumed. Both metrics reached thermal steady state in 40 min.

Fig. 6 shows the reported speed loss, estimated total perspiration, and core temperature rise for different ambient temperatures, which correspond to actual races in scenario (3). RH was assumed to be 50% because it is not always recorded and does not influence the resultant perspiration and core temperature rise for ambient temperatures lower than 25 °C, which is typical in the six marathons held in September (Berlin), October (Chicago), November (New York), and April (Boston, London, and Paris).

As shown in Fig. 6, the race speed has a peak at ambient temperatures of 5–10 °C, except for the top 1% of male athletes, in which a further lower temperature is expected. A reasonable correlation was observed between speed loss and perspiration or core temperature rise for the top 1% male athletes. Perspiration for the lower 25% athletes was larger than that for the top 1% athletes because of a longer race duration.

### D. ASSOCIATIONS BETWEEN THERMAL RESPONSE AND RUNNING SPEED IN WAC AND OLYMPIC GAMES

In the fourth scenario, for a total of 19 races in the WAC and Olympic Games, the actual ambient conditions were considered for the computed core temperature rise and perspiration in Fig. 7, assuming a metabolic rate of 13.3 METs. Unlike Fig. 6, the race speed obtained from [48] was not normalized because all races were held at different locations. Thus, the effects of height difference on course and wind speed were not considered because detailed information was not available for the latter. For comparison, the correlation of running speed with ambient temperature and WBGT is also shown in Fig. 7. These metrics are often used to evaluate marathon performance in related studies. Regression lines were derived as a quadratic function because this fitting provided a better correlation than a linear function in all cases.

As shown in Fig. 7, the estimated perspiration for male athletes provides better coefficients of determination, $R^2$, than ambient temperature and WBGT for the speeds of the 1st, 3rd, and 8th place winners. Specifically, the $R^2$ values for the perspiration and WBGT were 0.51 and 0.40, respectively, for male athletes. A similar tendency was observed for female athletes. However, perspiration and WBGT were comparable, except for the 1st place winners. One reason for the satisfactory performance of perspiration is the nonlinear thermoregulation of humans. For male athletes, a threshold for perspiration exists when the speed loss increases. However, no clear threshold exists for female athletes; the lesser the perspiration, the more the race speed. Although not shown here, the correlation between the race speed and the sweating rate was almost comparable but worse than that of the total perspiration. This is because the sweating rate is almost time-independent after 40 min. The correlation of running speed with all the parameters was statistically significant in male athletes ($p < 0.05$), except the ambient temperature, and all parameters for female athletes ($p < 0.001$).

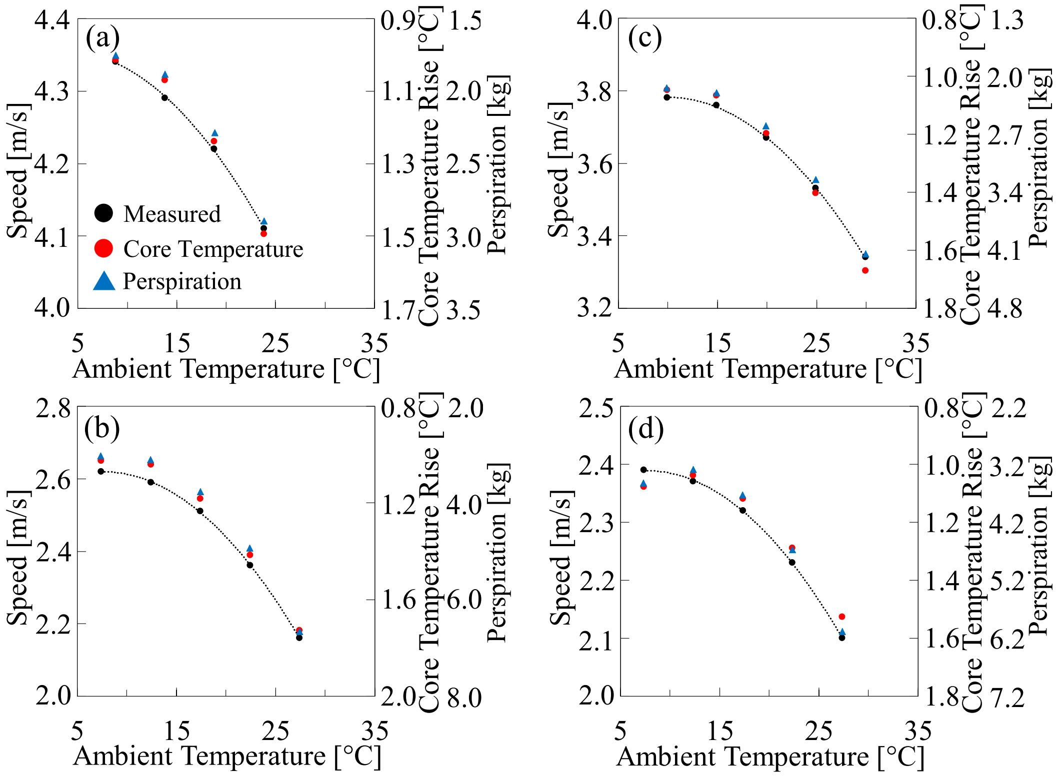

**FIGURE 6.** **Correlation between ambient temperature and average speed of (a, b) male athletes and (c, d) female athletes in six marathon races. (a) and (c) are the group of top 1% athletes, and (b) and (d) are the group of lowest 25%. The dashed lines show the quadratic polynomial regression curves in running speed. Core temperature rise and perspiration are estimated considering weather data and race time in each cluster and marathon race, and are also plotted. Measured values are obtained from [6].**

### *E. RELATIONSHIP OF COMPLETION RATE WITH AMBIENT FACTORS AND THERMOREGULATION*

Fig. 8 shows the completion rates for different ambient temperatures, WBGT, perspiration, and core temperature rise in the WAC and Olympic Games. The completion rates were obtained from [48]. As shown in Fig. 6, the tendencies vary between male and female athletes, which is similar to speed loss. For female athletes, strong correlations (>0.6–0.7) were observed between the completion rate and all ambient and thermo-physiological responses. The ambient temperature provided the highest correlation for quadratic approximation. Although not shown here, it was 0.5–0.7 for linear approximation. For male athletes, a weak or moderate correlation (0.2–0.5) exists for the same comparisons. The correlations of completion rate speed were statistically significant with WBGT and core temperature in male athletes ($p < 0.05$), while these correlations were significant with all metrics in female athletes ($p < 0.001$).

### *F. APPLICATION FOR UPCOMING OLYMPIC GAMES*

In the fifth scenario, we computed the core temperature rise and perspiration with the mean ambient conditions of Tokyo and Sapporo to simulate the conditions during the Summer 2020 Olympic Games in August. The thermo-physiological responses for the mean and worst cases were computed (listed in Table 1). Fig. 9 shows the time course of the core temperature and sweating rate in Tokyo and Sapporo. The core temperature rise and perspiration for mean ambient conditions after 130 min were 1.49 °C and 2.0 kg in Tokyo, and 1.28 °C and 1.7 kg in Sapporo, respectively. Meanwhile, the potential highest ambient conditions in the past 10 years were 1.89 °C and 2.5 kg in Tokyo, and 1.72 °C and 2.3 kg in Sapporo, respectively. The perspiration of the female athletes, which is more relevant to the speed loss, was almost equivalent to that of the male athletes: 2.9 kg in Tokyo and 2.4 kg in Sapporo for the mean condition, and 4.0 kg in Tokyo and 3.0 kg in Sapporo for the highest ambient condition after 150 min.

## V. DISCUSSION

In this pilot study, we explored the applicability of computed perspiration and core temperature rise to the estimation of speed loss and completion rate in marathon races. First, our computed results of core temperature rise and perspiration or water loss suggest that the computational estimation shows an agreement with the measured values reported in previous studies (scenarios (1) and (2)). The tendencies of core temperature and sweating rate were also confirmed for different ambient conditions. In general, both metrics attained a steady state after 35–45 min. These results are in agreement with

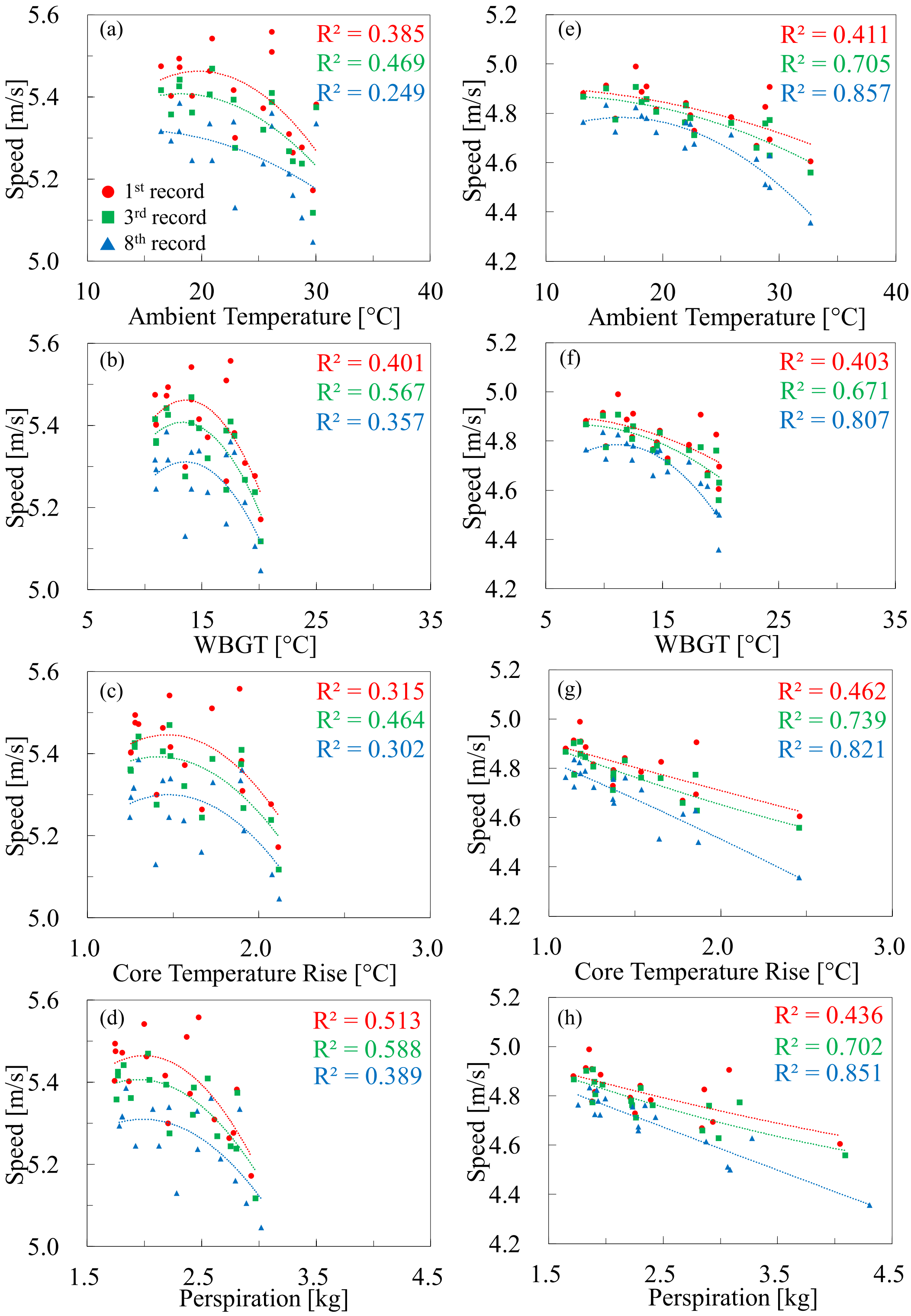

**FIGURE 7.** Relationship of running speed with (a, e) ambient temperature, (b, f) WBGT, (c, g) core temperature rise, and (d, h) perspiration in the WAC and Olympic Games. (a)-(d) and (e)-(h) represent the results of male and female athletes, respectively. The dashed lines show the quadratic polynomial regression curves in each result. For comparison, the results based on the 1st, 3rd, and 8th place winners are presented. The speed values are obtained from [48].

the measurements in [11]. The abovementioned time for the steady state is governed by the heat balance between the human body and the ambient conditions. We then presented a well-known mechanism for heat balance during exercise. The main factor behind heat loss against temperature rise was evaporative heat loss. The sweating response is nonlinear

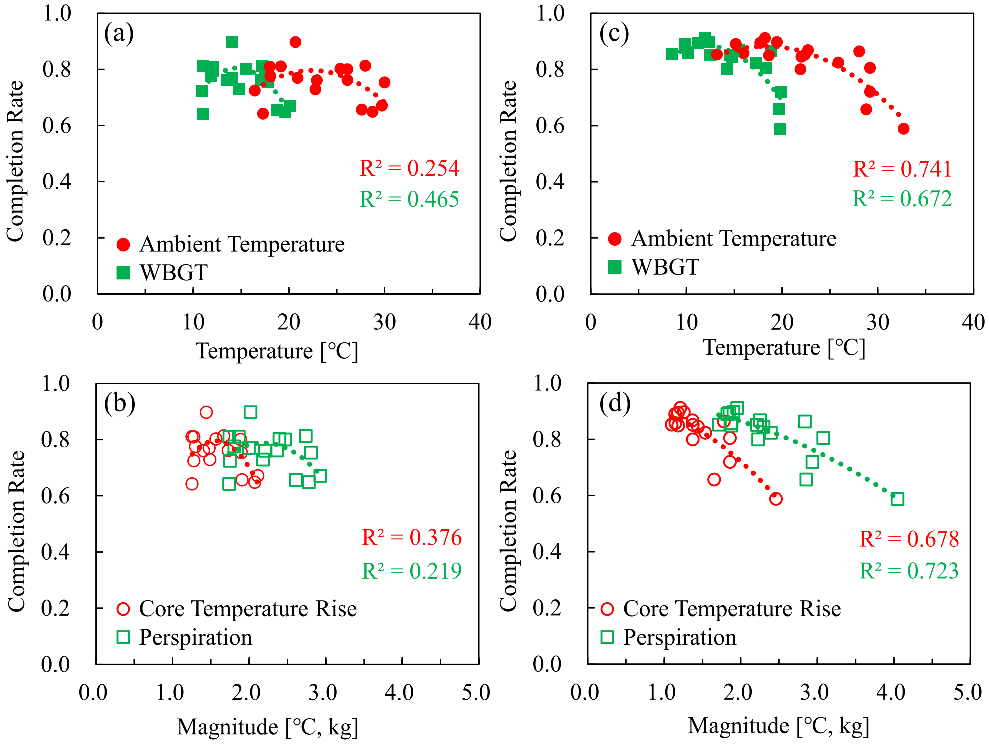

**FIGURE 8.** Effect of ambient temperature, WBGT, core temperature rise, and perspiration on completion rate in (a, b) male athletes and (c, d) female athletes in the WAC and Olympic Games. The dashed lines show the quadratic polynomial regression curves in each result. Completion rates are obtained from [48].

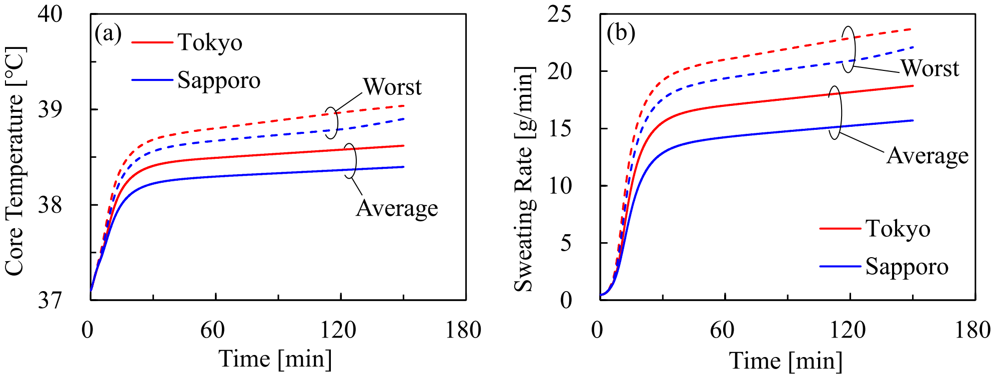

**FIGURE 9.** Estimated time course of core temperature and sweating rate in the male model during virtual marathon races held in Tokyo and Sapporo. (a) Core temperature and (b) sweating rate for mean ambient conditions on a sunny day and the highest ambient temperature were considered for comparison.

(refer to (3) and (4)); thus, a considerable amount of time is necessary to attain a steady state. A thermal time constant in the range of 40–60 min is suggested for a common heat load in the marathon race. In our study, the time taken to attain a steady state was comparable to but somewhat shorter than the value because of a high metabolic rate. Thus, the time taken to reach the highest sweating rate was short. As we can observe, our computational code based on the general population works well for group-level well-trained occupational (scenario 2) and general populations (scenario 1).

We extended our computation to estimate the speed loss under different ambient conditions. The computed results were compared with the speed loss derived from six races for 10 years. We discovered that the speed loss was strongly correlated with both the total perspiration and the core temperature rise, which is similar to the ambient conditions. The reason for the marginal difference between the perspiration and the core temperature rise is the relatively dry condition and fixed time duration (2 h and 10 min for top athletes). Sweat evaporates well under the considered conditions, although some nonlinearity exists. An additional uncertainty factor is age, as reported in [50], where the race speed becomes minimal for athletes aged 25–29 years. The effect of age in different sports has been discussed [50], [51], as well as the effects of race distance and gender [52]. In general, women differ from men in thermal responses because of a larger ratio of body surface to body mass, a greater subcutaneous fat content, and lower exercise capacity [1], [52]. Except for exercise capacity, the computational method presented in this study automatically considers these factors. Although the core temperature and water loss estimated from its extension to the general population agrees well with those of elite athletes, it does not imply that our computational modeling is fully applicable to elite athletes. Further studies are necessary to develop a suitable model for elite athletes.

The speed loss was evaluated for the same courses or six major races in [6]. Different courses may have elevation differences, leading to different metabolic rates while running the same distance. As shown in Fig. 6, core temperature and total perspiration were better metrics than were ambient temperature for male athletes, and vice versa for female athletes, where the conventional ambient temperature was better. As shown in Figs. 6 (c) and (d), the threshold values of core temperature rise and perspiration, at which the speed loss is observed, were 1.5 °C and 2.0–2.5 kg, respectively. No clear reason exists for a reduced race speed for a core temperature rise below 1.5 °C and perspiration less than 2.0–2.5 kg. As for the latter, it has been reported that a 2% water loss [53], which is approximately 1.0–1.3 kg, may result in degraded performance. Sharwood *et al.* [54] reported a weight loss of 1.6–4.6 kg during a race and a mild positive correlation between weight loss and performance time. Considering water intake (e.g., 1.4 kg in [12]), a threshold water loss of 0.6–1.1 kg is reasonable. This finding may suggest that the performance declines for conditions where perspiration and core temperature exceed the thresholds. This result may also be useful for planning races with course and weather information.

The curve for speed loss resembles the basal metabolic rate for ambient temperature [55], where the center frequency is 30 °C in a resting condition. Although not considered here, a speed loss for lower ambient temperatures can be expected owing to shivering and vasoconstriction at temperatures below 5–10 °C [6]. In addition, for strong winds during a race, both factors are case-specific; thus, considering them with high accuracy is difficult. Meanwhile, the thresholds of core temperature rise for excellent performance in the six races (1 °C) and the Olympic Games (1.5 °C) do not agree. This may be attributed to the differences within a month or the heat adaptation [56], [57]. Note that the thermoregulatory response model does not consider heat adaptation [58], [59] because of a lack of sufficient data for developing a thermal model for athletes.

Our computational results suggest that the completion rates in larger marathon races are marginally affected by the ambient conditions for men, but the WBGT is well correlated for women. This conclusion is different from that reported in [6], which was derived from the Chicago Marathon: the higher the ambient temperature, the lower the completion rate for men. Additionally, the differences between sexes would hypothesize the difference in thermoregulation [52]: a smaller body surface area and thicker fat layer in women, in addition to the sweating capacity. Even when the female and male models were deformed to consider the effect of the former two factors, the resulting core temperature and sweating differed by only 5%. This finding implies that sweating capacity is a dominant factor related to the completion rate. In [60], the authors concluded that a collapse because of hyperthermia and dehydration might cause cardiovascular strain and unstable subcutaneous blood pressure. However, this result was not supported by measurements, which suggest that the completion rate is also related to other factors, including injuries in the lower extremities [61] and musculoskeletal injuries [62].

We extend our discussion to estimate a race in the Olympic Games 2021. The differences among the estimated results for Tokyo and Sapporo were marginal for ambient conditions averaged over 10 years. A marginal difference between the two cities was observed when considering the day with the highest ambient temperature in the past 10 years, based on the estimated perspiration. For the mean ambient condition, a race pacing of 5.35 m/s is expected in Tokyo, whereas a race pacing of 5.45 m/s is expected in Sapporo. For the worst condition, these values may be reduced to 5.2 m/s and 5.3 m/s, respectively. Only a marginal difference can be expected in pacing, which is not notable between Tokyo and Sapporo.

A speed loss of 1% or less is also expected for female athletes. The completion rate for male athletes is rather insensitive to ambient conditions; thus, it is not discussed further. For this condition, female completion rates for the highest ambient temperature in Tokyo and Sapporo are estimated to be 0.65 and 0.71, respectively, which are comparable to those attained in previous competitions. For normal sunny days in Tokyo and Sapporo, the completion rates are 0.76 and 0.84, respectively.

The limitation of this study is in the computations, although they were validated with the data obtained in previous studies. The subjects were mainly general population (non-athletes). The thermoregulation for the athletes was partly validated in Fig. 2 but not sufficient due to the lack of measured data. More validation and/or extension to elite athletes remain as a future work.

In addition, typical values of metabolic rates in a marathon were assumed to be constant. Thus, the running speed during a final spurt may not be appropriately considered [11]. In reality, metabolic rate and ambient conditions may vary with time. If detailed weather conditions in the Olympic Games and WAC are available, the ambient conditions can be improved [42], although the time dependence (in the order of seconds or minutes) of wind velocity and microclimate in urban areas may be still challenging topics. Besides, the metabolic rates should be combined more accurately based on a heart rate peculiar to athletes [62].

The computation conducted in this study was validated for group-level test subjects rather than specific individuals. The estimation was then extended to specific athletes (winners of the race). If the individual assessments are performed with the time-dependent meteorological data during marathon race, additional physiological data at rest for the corresponding athletes (e.g., oxygen uptake, heart rate, etc.) are required. Such topics without the measurement at rest would be challenging, although they depend on the accuracy of wearable sensors. Future research on these measured data is required to ultimately extend this study to specific elite athletes.

## VI. CONCLUSION

In this study, we proposed a computational estimation of core temperature and perspiration related to the speed and competition rate in marathons. This study was the first to investigate the association between marathon performance and thermo-physiological response, which is a nonlinear problem associated with ambient conditions, by computations. The major findings are as follows: 1) The computed metrics provided a better correlation with speed loss in marathon races in men ($R^2 = 0.50$, $p < 0.05$) than with ambient temperature ($R^2 = 0.37$, not significant). 2) The completion rate has a moderate correlation with WBGT in male athletes ($R^2 = 0.47$, $p < 0.05$), whereas a strong correlation was observed for the ambient temperature in female athletes ($R^2 = 0.74$, $p < 0.001$). Note that the race data in intense heat is limited. In addition, the effect of location change in the upcoming 2020 Olympic Games was a marginal difference. Although more validation and/or extension of specific elite athletes is needed for the application of our approaches to race planning, our findings are useful for estimating race speed and completion rate for potential use in race planning and risk management in marathons. Furthermore, their application to other sports remains as a future work.

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