Impact of different climatic conditions on peak core temperature of elite athletes during exercise in the heat: a Thermo Tokyo simulation study

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ABSTRACT

Objectives To evaluate how separate and combined climatic parameters affect peak core temperature during exercise in the heat using computer simulations fed with individual data.

Methods The impact of eight environmental conditions on rectal temperature (T_r) was determined for exercise under heat stress using the Fiala-thermal-Physiology-and-Comfort simulation model. Variations in ambient temperature (T_a ±6°C), relative humidity (RH ±15%) and solar radiation (SR+921 W/m²) were assessed in isolation and combination (worst-case/best-case scenarios) and compared with baseline (T_a 32°C, RH 75%, SR 0 W/m²). The simulation model was fed with personal, anthropometric and individual exercise characteristics.

Results 54 athletes exercised for 46±10 min at baseline conditions and achieved a peak core temperature of 38.9±0.5°C. Simulations at a higher T_a (38°C) and SR (921 W/m²) resulted in a higher peak T_r compared with baseline (+0.6±0.3°C and +0.5±0.2°C, respectively), whereas a lower RH (90%) hardly affected peak T_r (+0.1±0.1°C). A lower T_a (26°C) and RH (60%) reduced peak T_r by −0.4±0.2°C and a minor −0.1±0.1°C, respectively. The worst-case simulation yielded a 1.5±0.4°C higher T_r than baseline and 2.0±0.7°C higher than the best-case condition.

Conclusion Combined unfavourable climatic conditions produce a greater increase in peak core temperature than the sum of its parts in elite athletes exercising in the heat.

Key messages

What is already known
− The magnitude of exercise-induced increases in core temperature and subsequent performance loss or health risks depends on the severity of climatic conditions.
− Elite athletes are recommended to participate in heat preparedness programs before competition in hot and humid environments, such as the Tokyo 2020 Olympic Games. Still, actual climatic conditions may vary from the simulated conditions.

What are the new findings
− Realistic variations in air temperature, relative humidity (RH) and solar radiation (SR) have distinct effects on the estimated peak core temperature of elite athletes exercising in the heat.
− The worst-case scenario simulation (T_a 37.5°C; RH: 79%; SR: 921 W/m²) predicted a peak T_r of 40.3±1.0°C after 46±10 min of high-intensity exercise, with 56% of the athletes demonstrating a T_r >40°C and 17% a T_r >41°C.
− The combination of unfavourable climatic conditions led to a synergistic response with a greater effect on T_r than the sum of its parts, highlighting the added value of computer modelling beyond physiological testing in an environmental chamber.

INTRODUCTION

The Tokyo Olympic and Paralympic Games were organised under challenging climatic conditions. Analyses of historical data revealed that an ambient temperature (T) of 31.3±3.1°C and relative humidity (RH) of 59±10% were expected around noon, whereas solar radiation (SR) could exceed 900 W/m². These environmental conditions accelerate exercise-induced increases in core temperature (T_c), which is known to negatively impact exercise performance and increase the risk for the development of heat-related illnesses. Therefore, preparatory testing for Tokyo 2020 was recommended by experts, and many countries implemented heat preparation programmes for their Olympic teams.

The Dutch Olympic Team launched the Thermo Tokyo program, in which individual heat tolerance was determined during an exercise test in simulated Tokyo conditions. Although such tests provide useful insight into the responses to a hot humid climate in general, climatic conditions may vary from day to day, and changes in T_c, RH and SR are known to impact human thermoregulation. As it is not feasible to subject elite athletes to exercise testing across a large variety of
climatic conditions, we aimed to evaluate the impact of various Tokyo summer climatic conditions on T<sub>e</sub> responses using computer simulations of the individual exercise tests, fed with individual athlete data.

**METHODS**

**Study cohort and design**

This is a substudy of the Thermo Tokyo project of which the rationale, design and measurements have been described in detail previously. In short, Dutch outdoor athletes (≥16 years) were recruited via TeamNL infrastructure. All athletes were active at the elite level as they competed at international tournaments and top-level competitions. Detailed anthropometric measurements were conducted, and all athletes completed an incremental cycling test until volitional exhaustion in simulated Tokyo conditions (T<sub>a</sub> 32°C, RH 75%). Data from 54 participants (14 endurance-trained, 8 mixed-trained, 12 power-trained and 20 skill-trained athletes) were used to feed the thermophysiological simulation model in order to assess the impact of distinct climatic conditions on peak T<sub>e</sub>.

**Data collection**

Anthropometric characteristics were derived from a DXA scan (Discovery-A, Hologic, Bedford, USA) and a full-body 3D scan (Artec 3D, Luxembourg). Height, weight, fat percentage and characteristics of 24 body segments were derived from these measurements. Gastrointestinal temperature (T<sub>gi</sub>) and power output (W) were continuously measured during the exercise test using the myTemp system and a bicycle ergometer (Lode B.V., Groningen, Netherlands) or Tacx Neo Smart T2800 (Tacx B.V., Wassenaar, Netherlands), respectively. Finally, the time to exhaustion of the incremental exercise test was established.

**Computer simulation**

The validated Fiala-thermal-Physiology-and-Comfort (FPC) simulation model (V.5.4) was used to model the impact of eight different environmental conditions (table 1) on rectal temperature (T<sub>e</sub>). Individual characteristics (sex, age, VO<sub>2max</sub>, acclimatisation status), anthropometrics and exercise intensities during the test (metabolic equivalent of task score (METs), calculated from power output) served as input for the model. First, the baseline condition was modelled to reproduce the physiological responses collected during the exercise test in the climatic chamber. Then, simulations with adjustments in T<sub>a</sub> (±6°C), RH (±15%) and SR (+921 W/m<sup>2</sup>) were conducted. Finally, a best-case and worst-case scenario simulation was conducted based on the 95% CI boundaries for the expected T<sub>a</sub>, RH and SR at noon during the Tokyo Olympics.

Wind speed was kept constant at standard airflow of 0.2 m/s; convective cooling by pedalling movements was accounted for by an adjusted airflow of 1.0 m/s at the legs). An average gross efficiency factor of 0.2 was used. Standardised clothing settings were selected for shirt and shorts. Peak T<sub>e</sub> was used as the primary outcome. The reduction in the time to reach the peak T<sub>e</sub> attained in the baseline simulation was included as a secondary outcome parameter.

**RESULTS**

Fifty-four elite athletes (53.7% female) participated in this Thermo Tokyo substudy, and all data were collected successfully. Characteristics of the study cohort are summarised in table 2.

**Model performance**

A peak T<sub>e</sub> of 38.9±0.5°C was measured at the end of the exercise test in the environmental chamber. Computer simulations using the FPC model yielded an estimated peak T<sub>e</sub> of 38.8±0.6°C at baseline conditions (T<sub>a</sub> 32°C, RH 75%, no SR). Accordingly, the difference between the measured versus simulated peak core temperatures was −0.1±0.5°C.

**Impact of climatic conditions**

A typical example of exercise-induced changes in T<sub>e</sub> of an individual athlete for each of the eight climatic conditions in the FPC simulations is shown in figure 1. On a group level, a higher T<sub>e</sub> was predicted following exercise in the condition with a 6°C higher T<sub>a</sub> (+0.6±0.3°C) and the condition with maximal SR (+0.5±0.2°C) compared with the baseline condition. Peak T<sub>e</sub> of the baseline condition was attained 9±7 and 9±8 min earlier in these respective conditions. A 15% increase or decrease in RH resulted in a lower peak T<sub>e</sub> than baseline (−0.4±0.2°C). A 6°C lower T<sub>a</sub> resulted in a lower peak T<sub>e</sub> than baseline (−0.4±0.2°C). Peak T<sub>e</sub> was 1.5±0.4°C higher in the worst-case scenario compared with the baseline condition, with an absolute predicted value of 40.3±1.0°C. As many as 56% of the athletes had a peak T<sub>e</sub> >40°C, and 17% had a peak T<sub>e</sub> >41°C. Furthermore, peak T<sub>e</sub> was attained 19±6 min

### Table 1 Summary of the eight distinct environmental conditions that were entered into the Fiala-thermal-Physiology-and-Comfort simulation model

| Simulations | T<sub>a</sub> (°C) | RH (%) | V<sub>aw</sub> (m/s) | Rad (W/m<sup>2</sup>) |
|-------------|----------------|--------|----------------|-----------------|
| Baseline    | 32             | 75     | 0.2            | 0               |
| Higher T<sub>a</sub> | 38             | 75     | 0.2            | 0               |
| Lower T<sub>a</sub> | 26             | 75     | 0.2            | 0               |
| Higher RH   | 32             | 90     | 0.2            | 0               |
| Lower RH   | 32             | 60     | 0.2            | 0               |
| Radiation  | 32             | 75     | 0.2            | 921             |
| Worst case | 37.5           | 79     | 0.2            | 921             |
| Best case  | 25.1           | 39     | 0.2            | 0               |

Rad, radiation; RH, relative humidity; T<sub>a</sub>, ambient temperature; V<sub>aw</sub>, air flow; W, watt.
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(41%±13%) earlier during exercise in worst-case conditions. The best-case simulation yielded a 0.5±0.3°C lower \( T_r \) than baseline and 2.0±0.7°C lower \( T_r \) than the worst-case condition. An overview of all FPC model predictions is summarised in figure 2.

DISCUSSION

This simulation study showed that small to moderate variations in climatic conditions could considerably impact the peak \( T_r \) of elite athletes exercising in the heat. A 6°C increase in \( T_a \), or the addition of high-intensity SR contributed to an accelerated exercise-induced \( T_r \). In contrast, the impact of variations in RH on peak \( T_r \) was limited. Beyond the effect of isolated climatic conditions, the worst-case model highlighted that a combination of heat stressors leads to more significant heat stress, evidenced by predicted peak \( T_r \) values >40°C in 56% of the elite athletes. Therefore, the outcomes of this study provide important insight into the thermoregulatory responses of elite athletes during exercise under various challenging climatological conditions.

FPC model

We used the FPC model to simulate the impact of different climatic conditions on \( T_r \). After feeding the model with physiological and anthropometric data for every individual athlete that participated in the present study,7 13 the average difference between the measured and predicted \( T_r \) for baseline climatic conditions was acceptably small (−0.1±0.5°C). Hence, we used these FPC settings to simulate the remaining conditions.

Climatic conditions

We found a substantial variability of peak \( T_r \) across the simulated climatic conditions. The greatest increase in peak \( T_r \) was observed at a 6°C increase in \( T_a \). This finding aligns with a recent study in which \( T_a \) was the most important climatic parameter to affect peak performance during endurance running events.20 We also found that the impact of \( T_a \) on predicted \( T_r \) was not linear, as a 6°C decrease in \( T_a \) had less effect on peak \( T_r \) compared with a 6°C increase in \( T_a \) (−0.4±0.2 vs +0.6±0.3). These observations stress the added value of computer simulations beyond exercise tests with physiological measurements, as proper predictions can optimise heat mitigation strategies across multiple scenarios of climatic conditions. Maximal SR appeared to have a large effect on peak \( T_r \). This is in line with previous research, indicating a significant increase in the body’s heat gain with increasing radiation intensity.21

In contrast to our hypothesis and existing literature,5 we found little impact of variations in RH on peak \( T_r \). This may be due to the small magnitude of RH variations (±15%).

### Table 2 Characteristics of the complete cohort as well as sex-specific groups

| Characteristic                  | Total cohort | Male athletes | Female athletes | Endurance trained athletes | Power trained athletes | Skill trained athletes | Mixed trained athletes |
|--------------------------------|--------------|---------------|----------------|---------------------------|-----------------------|-----------------------|-----------------------|
| **N**                          | 54           | 25            | 29             | 14                        | 12                    | 20                    | 8                     |
| **Age (year)**                 | 25±4         | 25±4          | 25±4           | 23±5                      | 23±3                  | 25±4                  | 29±4                  |
| **VO2max** (mL/kg/min)**       | 41±11        | 43±11         | 39±11          | 56±6                      | 40±4                  | 31±4                  | 40±3                  |
| **Height (cm)**                | 178±10       | 185±9         | 171±6          | 174±10                    | 176±8                 | 178±7                 | 186±15                |
| **Weight (kg)**                | 75±13        | 83±11         | 69±10          | 64±10                     | 79±10                 | 78±11                 | 81±13                 |
| **Fat content (%)**            | 18±6         | 13±5          | 22±5           | 16±5                      | 15±6                  | 23±5                  | 15±6                  |
| **Time to exhaustion (min)**  | 46±10        | 43±10         | 48±8           | 50±10                     | 44±5                  | 44±11                 | 45±10                 |
| **Peak power output (W)**      | 190±51       | 226±47        | 160±32         | 274±50                    | 240±51                | 170±25                | 251±57                |

*Peak power output and subsequently derived VO2max values have been attenuated due to the long trial duration, strenuous climatic conditions and athlete sport type.13

Figure 1 Typical outcome of the computer simulation of a single participant, with exercise-induced increases in rectal temperature for each of the eight simulated climatic conditions. \( T_a \) ambient temperature; RH, relative humidity; SR, solar radiation.

Figure 2 Overview of all FPC model predictions with exercise-induced increases in rectal temperature for each of the eight simulated climatic conditions.
and/or the low wind speed, limiting the possibility to evaporate sweat. Indeed, variations in RH between 52% and 71% have previously been shown not to result in significant changes in Tre during a 1-hour steady state run with little air flow.22 In addition, a change in skin temperature may potentially affect the impact of RH variations on heat loss. For example, increases in skin temperature at +15% RH or decreases in skin temperature with −15% RH may attenuate the heat loss effect due to the altered water vapour pressure difference between skin and environment. This could have contributed to the low impact of RH level in the current study but needs to be confirmed in future studies as skin temperature was unavailable in our simulations.

Practical application
We showed that computer modelling of exercise-induced increases in Tre provides additional insights beyond physiological testing in an environmental chamber. Hence, this approach may be adopted in preparation for future World Championships, Olympic Games and other exercise events in environmentally stressful conditions. Computer simulations provide athletes and coaches unique insight into changes in individual thermophysiological and performance indicators across different climatic scenarios without the burden of extensive exercise testing. Hence, this information can be used to select the most appropriate precooling/percooling strategies, hydration plan and race strategy.

Strengths and limitations
Strengths of the study include the large sample size (n=54) and a large number of simulations (8 distinct conditions) to assess the impact of variations in the Tokyo climate on the predicted Tre of Olympic athletes. This study, however, is also subject to limitations. First, we assumed a similar exertional heat production across climatic conditions, whereas athletes will generally adjust their pacing in an anticipatory way dependent on conditions, potentially affecting their physiological responses. Further, the wind speed was kept stable in this study, whereas it would have been interesting to explore the thermal impact of sport-specific wind speeds. Nevertheless, our results highlight the impact of different realistic climatic scenarios on the thermal strain, and the consequences if preparatory measures and anticipatory signals are not taken seriously.

CONCLUSION
Isolated climatic conditions, such as a higher Ta and high SR, significantly increase peak Tre in elite athletes exercising in the heat. Moreover, the combination of unfavourable climatic conditions in a worst-case scenario led to a synergistic response with a greater effect on Tre than the sum of its parts.

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REFERENCES
1 Gerrett N, Kingma BRM, Sluijter R, et al. Ambient conditions prior to Tokyo 2020 Olympic and Paralympic games: considerations for acclimation or acclimatization strategies. Front Physiol 2019;10:414.
2 Périaud JD, Eijsvogels TMH, Daanen HAM. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. *Physiol Rev* 2021;101:1873–97.

3 Galloway SD, Maughan RJ. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Med Sci Sports Exerc* 1997;29:1240–9.

4 Hettinga FJ, De Koning JJ, de Vrijer A, et al. The effect of ambient temperature on gross-efficiency in cycling. *Eur J Appl Physiol* 2007;101:465–71.

5 Maughan RJ, Otani H, Watson P. Influence of relative humidity on prolonged exercise capacity in a warm environment. *Eur J Appl Physiol* 2012;112:2313–21.

6 Tatterson AJ, Hahn AG, Martin DT, et al. Effects of heat stress on physiological responses and exercise performance in elite cyclists. *J Sci Med Sport* 2000;3:186–93.

7 de Korte JQ, Bongers CCWG, Hopman MTE, et al. Exercise performance and thermoregulatory responses of elite athletes exercising in the heat: outcomes of the thermo Tokyo study. *Sports Med* 2021;51:2423–36.

8 Cooper ER, Ferrara MS, Broglio SP. Exertional heat illness and environmental conditions during a single football season in the Southeast. *J Athl Train* 2006;41:332–6.

9 Racinais S, Ihsan M. Why should I test my athletes in the heat several months before Tokyo 2020? *J Therm Biol* 2021;99:102975.

10 Clarsen B, Steffen K, Berge HM, et al. Methods, challenges and benefits of a health monitoring programme for Norwegian Olympic and Paralympic athletes: the road from London 2012 to Tokyo 2020. *Br J Sports Med* 2021;55:1342–9.

11 Eijsvogels TMH, de Korte JQ, Bongers CCWG. Beat the heat: how to become a gold medalist at the Tokyo Olympics. *Temperature* 2021;8:203–5.

12 Muniz-Pardos B, Angeloudis K, Guppy FM, et al. Wearable and telemedicine innovations for Olympic events and elite sport. *J Sports Med Phys Fitness* 2021;61:1061–72.

13 de Korte JQ, Bongers CCWG, Hopman MTE, et al. Performance and thermoregulation of Dutch Olympic and Paralympic athletes exercising in the heat: Rationale and design of the Thermo Tokyo study. The journal *Temperature* toolbox. *Temperature* 2021;8:209–22.

14 Lei T-H, Wang F, of Lahead. Looking ahead of 2021 Tokyo summer Olympic games: how does humid heat affect endurance performance? Insight into physiological mechanism and heat-related illness prevention strategies. *J Therm Biol* 2021;39:102975.