


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

Lennart P J Teunissen,<sup>1</sup> Kaspar M B Jansen,<sup>1</sup> Emiel Janssen,<sup>1</sup> Boris R M Kingma,<sup>2</sup> Johannus Q de Korte,<sup>3</sup> Thijs M H Eijsvogels <sup>3</sup>

**To cite:** Teunissen LPJ, Jansen KMB, Janssen E, *et al.* Impact of different climatic conditions on peak core temperature of elite athletes during exercise in the heat: a Thermo Tokyo simulation study. *BMJ Open Sport & Exercise Medicine* 2022;**8**:e001313. doi:10.1136/bmjsem-2022-001313

Accepted 15 June 2022



© Author(s) (or their employer(s)) 2022. Re-use permitted under CC BY. Published by BMJ.

<sup>1</sup>Department of Design Engineering, Delft University of Technology, Delft, The Netherlands

<sup>2</sup>Department of Training & Performance Innovations, TNO, Unit Defence, Safety & Security, Soesterberg, The Netherlands

<sup>3</sup>Radboud Institute for Health Sciences, Department of Physiology, Radboud University Medical Center, Nijmegen, The Netherlands

## Correspondence to

Dr Thijs M H Eijsvogels; thijs.eijsvogels@radboudumc.nl

## 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 ( $T_{re}$ ) was determined for exercise under heat stress using the Fiala-thermal-Physiology-and-Comfort simulation model. Variations in ambient temperature ( $T_a \pm 6^\circ\text{C}$ ), relative humidity (RH  $\pm 15\%$ ) and solar radiation (SR  $+921 \text{ W/m}^2$ ) were assessed in isolation and combination (worst-case/best-case scenarios) and compared with baseline ( $T_a 32^\circ\text{C}$ , RH 75%, SR 0  $\text{W/m}^2$ ). The simulation model was fed with personal, anthropometric and individual exercise characteristics.

**Results** 54 athletes exercised for  $46 \pm 10$  min at baseline conditions and achieved a peak core temperature of  $38.9 \pm 0.5^\circ\text{C}$ . Simulations at a higher  $T_a$  ( $38^\circ\text{C}$ ) and SR ( $921 \text{ W/m}^2$ ) resulted in a higher peak  $T_{re}$  compared with baseline ( $+0.6 \pm 0.3^\circ\text{C}$  and  $+0.5 \pm 0.2^\circ\text{C}$ , respectively), whereas a higher RH (90%) hardly affected peak  $T_{re}$  ( $+0.1 \pm 0.1^\circ\text{C}$ ). A lower  $T_a$  ( $26^\circ\text{C}$ ) and RH (60%) reduced peak  $T_{re}$  by  $-0.4 \pm 0.2^\circ\text{C}$  and a minor  $-0.1 \pm 0.1^\circ\text{C}$ , respectively. The worst-case simulation yielded a  $1.5 \pm 0.4^\circ\text{C}$  higher  $T_{re}$  than baseline and  $2.0 \pm 0.7^\circ\text{C}$  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.

## INTRODUCTION

The Tokyo Olympic and Paralympic Games were organised under challenging climatic conditions. Analyses of historical data revealed that an ambient temperature ( $T_a$ ) of  $31.3 \pm 3.1^\circ\text{C}$  and relative humidity (RH) of  $59\% \pm 10\%$  were expected around noon,<sup>1</sup> whereas solar radiation (SR) could exceed  $900 \text{ W/m}^2$ . These environmental conditions accelerate exercise-induced increases in core temperature ( $T_c$ ),<sup>2</sup> which is known to negatively impact exercise performance<sup>3–7</sup> and increase the risk for the development of

## 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 ( $T_a 37.5^\circ\text{C}$ ; RH: 79%, SR:  $921 \text{ W/m}^2$ ) predicted a peak  $T_{re}$  of  $40.3 \pm 1.0^\circ\text{C}$  after  $46 \pm 10$  min of high-intensity exercise, with 56% of the athletes demonstrating a  $T_{re} > 40^\circ\text{C}$  and 17% a  $T_{re} > 41^\circ\text{C}$ .
- ⇒ The combination of unfavourable climatic conditions led to a synergistic response with a greater effect on  $T_{re}$  than the sum of its parts, highlighting the added value of computer modelling beyond physiological testing in an environmental chamber.

heat-related illnesses.<sup>8</sup> Therefore, preparatory testing for Tokyo 2020 was recommended by experts,<sup>9</sup> and many countries implemented heat preparation programmes for their Olympic teams.<sup>10–12</sup>

The Dutch Olympic Team launched the Thermo Tokyo program, in which individual heat tolerance was determined during an exercise test in simulated Tokyo conditions.<sup>13</sup> 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  $T_a$ , RH and SR are known to impact human thermoregulation.<sup>14</sup> 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  $T_c$  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.<sup>13</sup> In short, Dutch outdoor athletes ( $\geq 16$  years) were recruited via TeamNL infrastructures. All athletes were active at the elite level as they competed at international tournaments and top-level competitions.<sup>15</sup> Detailed anthropometric measurements were conducted, and all athletes completed an incremental cycling test until volitional exhaustion in simulated Tokyo conditions ( $T_a$  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  $T_c$ .

### 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 ( $T_{gi}$ ) and power output (W) were continuously measured during the exercise test using the myTemp system<sup>16</sup> 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)<sup>17,18</sup> was used to model

the impact of eight different environmental conditions (table 1) on rectal temperature ( $T_{re}$ ). Individual characteristics (sex, age,  $VO_{2max}$ , acclimatisation status), anthropometrics and exercise intensities during the test (metabolic equivalent of task score (METs), calculated from power output)<sup>19</sup> 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  $T_a$  ( $\pm 6^\circ\text{C}$ ), RH ( $\pm 15\%$ ) 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  $T_a$ , RH and SR at noon during the Tokyo Olympics.<sup>1</sup> Wind speed was kept constant at exercise test conditions in the climatic chamber (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  $T_{re}$  was used as the primary outcome. The reduction in the time to reach the peak  $T_{re}$  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  $T_{gi}$  of  $38.9 \pm 0.5^\circ\text{C}$  was measured at the end of the exercise test in the environmental chamber. Computer simulations using the FPC model yielded an estimated peak  $T_{re}$  of  $38.8 \pm 0.6^\circ\text{C}$  at baseline conditions ( $T_a$  32°C, RH 75%, no SR). Accordingly, the difference between the measured versus simulated peak core temperatures was  $-0.1 \pm 0.5^\circ\text{C}$ .

### Impact of climatic conditions

A typical example of exercise-induced changes in  $T_{re}$  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  $T_{re}$  was predicted following exercise in the condition with a 6°C higher  $T_a$  ( $+0.6 \pm 0.3^\circ\text{C}$ ) and the condition with maximal SR ( $+0.5 \pm 0.2^\circ\text{C}$ ) compared with the baseline condition. Peak  $T_{re}$  of the baseline simulation was attained  $9 \pm 7$  and  $9 \pm 8$  min earlier in these respective conditions. A 15% increase or decrease in RH had little effect on peak  $T_{re}$  ( $+0.1 \pm 0.1^\circ\text{C}$  and  $-0.1 \pm 0.1^\circ\text{C}$ , respectively), and the time to reach baseline peak  $T_{re}$  was only  $2 \pm 9$  min shorter in the +15% condition. A 6°C lower  $T_a$  resulted in a lower peak  $T_{re}$  than baseline ( $-0.4 \pm 0.2^\circ\text{C}$ ). Peak  $T_{re}$  was  $1.5 \pm 0.4^\circ\text{C}$  higher in the worst-case scenario compared with the baseline condition, with an absolute predicted value of  $40.3 \pm 1.0^\circ\text{C}$ . As many as 56% of the athletes had a peak  $T_{re} > 40^\circ\text{C}$ , and 17% had a peak  $T_{re} > 41^\circ\text{C}$ . Furthermore, peak  $T_{re}$  was attained  $19 \pm 6$  min

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

Simulations	$T_a$ (°C)	RH (%)	$V_{air}$ (m/s)	Rad (W/m <sup>2</sup> )
Baseline	32	75	0.2	0
Higher $T_a$	38	75	0.2	0
Lower $T_a$	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;  $T_a$ , ambient temperature;  $V_{air}$ , air flow; W, watt.

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

	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
VO <sub>2max</sub> (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 VO<sub>2max</sub> values have been attenuated due to the long trial duration, strenuous climatic conditions and athlete sport type.<sup>13</sup>

(41%±13%) earlier during exercise in worst-case conditions. The best-case simulation yielded a 0.5±0.3°C lower T<sub>re</sub> than baseline and 2.0±0.7°C lower T<sub>re</sub> 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<sub>re</sub> of elite athletes exercising in the heat. A 6°C increase in T<sub>a</sub> or the addition of high-intensity SR contributed to an accelerated exercise-induced T<sub>re</sub>. In contrast, the impact of variations in RH on peak T<sub>re</sub> 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<sub>re</sub> 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.

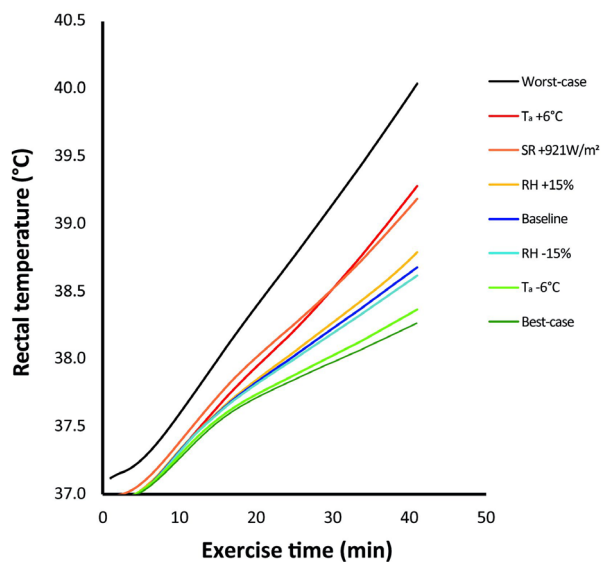
## FPC model

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

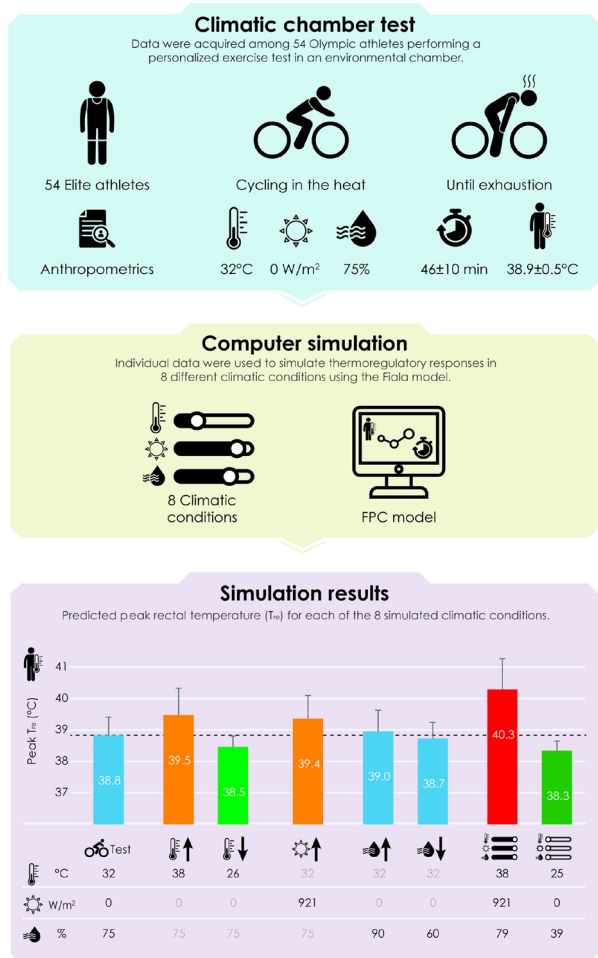
## Climatic conditions

We found a substantial variability of peak T<sub>re</sub> across the simulated climatic conditions. The greatest increase in peak T<sub>re</sub> was observed at a 6°C increase in T<sub>a</sub>. This finding aligns with a recent study in which T<sub>a</sub> was the most important climatic parameter to affect peak performance during endurance running events.<sup>20</sup> We also found that the impact of T<sub>a</sub> on predicted T<sub>re</sub> was not linear, as a 6°C decrease in T<sub>a</sub> had less effect on peak T<sub>re</sub> compared with a 6°C increase in T<sub>a</sub> (-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<sub>re</sub>. This is in line with previous research, indicating a significant increase in the body's heat gain with increasing radiation intensity.<sup>21</sup>

In contrast to our hypothesis and existing literature,<sup>5</sup> we found little impact of variations in RH on peak T<sub>re</sub>. This may be due to the small magnitude of RH variations (±15%)



**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<sub>a</sub>, ambient temperature; RH, relative humidity; SR, solar radiation.



**Figure 2** Outcomes of the computer simulation of eight distinct climatic conditions on peak rectal temperature ( $T_{re}$ ) of elite athletes exercising in the heat. An isolated increase in air temperature and solar radiation led to a higher peak  $T_{re}$ , but the impact of the worst-case scenario on peak  $T_{re}$  was greater than the sum of its parts. FPC, Fiala-thermal-Physiology-and-Comfort.

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  $T_{re}$  during a 1-hour steady state run with little air flow.<sup>22</sup> 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  $T_{re}$  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/per-cooling strategies,<sup>23</sup> hydration plan<sup>24</sup> 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  $T_{re}$  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,<sup>25</sup> 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  $T_a$  and high SR, significantly increase peak  $T_{re}$  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  $T_{re}$  than the sum of its parts.

**Acknowledgements** The authors would like to recognize the help of Bert Naagen, Toon Huysmans, Federico Altobelli, Shiannah Danen, Laura de Kubber and Jan-Willem van Dijk with data collection for the present study.

**Contributors** LT, KJ and TE designed the study. LT, BK, JdK and TE contributed to the data collection and analyses. EJ, LT and TE created the figures. LT and TE drafted the manuscript, while KJ, EJ, BK and JdK critically revised the manuscript. All authors gave their final approval of the version published.

**Funding** This project was funded by ZonMW (#546001003).

**Competing interests** None declared.

**Patient consent for publication** Consent obtained directly from patient(s).

**Ethics approval** This study was approved by CMO region Arnhem-Nijmegen (#2018-4640). Participants gave informed consent to participate in the study before taking part.

**Provenance and peer review** Not commissioned; externally peer reviewed.

**Open access** This is an open access article distributed in accordance with the Creative Commons Attribution 4.0 Unported (CC BY 4.0) license, which permits others to copy, redistribute, remix, transform and build upon this work for any purpose, provided the original work is properly cited, a link to the licence is given, and indication of whether changes were made. See: <https://creativecommons.org/licenses/by/4.0/>.

### ORCID iD

Thijs M H Eijvogels <http://orcid.org/0000-0003-0747-4471>

### REFERENCES

- 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 Périard JD, Eijsvogels TMH, Daanen HAM. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. *Physiol Rev* 2021;101:1873–979.
- 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 Tattersson 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? *Br J Sports Med* 2020;54:700–1.
- 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;99:102975.
- 15 McKay AKA, Stellingwerff T, Smith ES, et al. Defining training and performance caliber: a participant classification framework. *Int J Sports Physiol Perform* 2022;17:317–31.
- 16 Bongers CCWG, Hopman MTE, Eijsvogels TMH. Validity and reliability of the myTemp ingestible temperature capsule. *J Sci Med Sport* 2018;21:322–6.
- 17 Fiala D, Psikuta A, Jendritzky G, et al. Physiological modeling for technical, clinical and research applications. *Front Biosci* 2010;2:939–68.
- 18 Psikuta A, Fiala D, Laschewski G, et al. Validation of the Fiala multi-node thermophysiological model for UTCI application. *Int J Biometeorol* 2012;56:443–60.
- 19 Ainsworth BE, Haskell WL, Herrmann SD. The Compendium of Physical Activities Tracking Guide: Healthy Lifestyles Research Center. College of Nursing & Health Innovation, Arizona State University; 2011, 2020. Available: <https://sites.google.com/site/compendiumofphysicalactivities> [Accessed 03 Mar 2020].
- 20 Mantzios K, Ioannou LG, Panagiotaki Z, et al. Effects of weather parameters on endurance running performance: Discipline-specific analysis of 1258 races. *Med Sci Sports Exerc* 2022;54:153–61.
- 21 Bröde P, Kuklane K, Candas V, et al. Heat gain from thermal radiation through protective clothing with different insulation, reflectivity and vapour permeability. *Int J Occup Saf Ergon* 2010;16:231–44.
- 22 Che Muhamed AM, Atkins K, Stannard SR, et al. The effects of a systematic increase in relative humidity on thermoregulatory and circulatory responses during prolonged running exercise in the heat. *Temperature* 2016;3:455–64.
- 23 Bongers CCWG, Hopman MTE, Eijsvogels TMH. Cooling interventions for athletes: an overview of effectiveness, physiological mechanisms, and practical considerations. *Temperature* 2017;4:60–78.
- 24 Périard JD, Eijsvogels T, Daanen HAM, et al. Hydration for the Tokyo Olympics: to thirst or not to thirst? *Br J Sports Med* 2021;55:410–1.
- 25 Tucker R, Marle T, Lambert EV, et al. The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. *J Physiol* 2006;574:905–15.