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ORIGINAL INVESTIGATION

Factors Associated With Performance Decrements in Elite Athletes During Exercise Under Hot and Humid Ambient Conditions

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Purpose: Exercise performance is compromised in hot and humid conditions compared to temperate circumstances. However, it remains unclear which factors predispose individuals to either small or large performance decrements. This study aimed to identify factors associated with performance decrements in elite athletes during exercise under hot and humid ambient conditions. *Methods:* One hundred and six Dutch elite athletes performed a standardized incremental exercise test in a temperate condition (TEMP, ambient temperature 15.9 °C [1.2 °C], and relative humidity 55% [6%]) and hot—humid condition (HOT, ambient temperature 31.6 °C [1.0 °C], and relative humidity 74% [5%]). Performance loss was determined by the relative difference in time to exhaustion between both conditions. Multivariable linear regression analyses were performed to determine the association between performance loss and athlete characteristics, exercise responses, thermoregulatory responses, and perceptual parameters. *Results:* Time to exhaustion decreased from 60 (14) minutes in TEMP to 44 (10) minutes in HOT, corresponding to an average performance decrement of 26% (11%). Higher dehydration rates and more thermal discomfort in TEMP were associated with greater performance decrements. On the other hand, a higher BMI, female sex, greater exercise-induced increases in core temperature (T_C) in HOT, and a higher peak heart rate (HR) and exercise-induced increases in HR in HOT versus TEMP were associated with less performance decrements (adjusted $R^2 = .58$; $P < .001$). *Conclusion:* We identified that variables related to exercise responses (ie, HR, dehydration), athlete characteristics (ie, BMI, sex), thermoregulatory responses (ie, T_C), and perception (ie, thermal discomfort) were associated with performance decrements during exercise in the heat. Our multivariable regression model explained 58% of the magnitude of performance decrements.

Keywords: environmental conditions, exercise-induced hyperthermia, exercise performance, heat stress, performance loss

Exercise under hot and humid ambient conditions challenges homeostasis of the human body. The combination of environmental heat stress and exercise-induced metabolic heat production often leads to profound elevations in core temperature (T_C), skin temperature (T_{sk}), heart rate (HR), and whole body sweat rate (WBSR).[1] These (thermo)physiological responses may cause thermal discomfort and performance loss compared to exercise in cooler conditions. However, the magnitude of environmental-induced performance loss appears to be heterogeneous, since large differences in performance decrements during exercise in the heat were reported in previous studies (range: 2%–39%), indicating large interindividual variability which cannot be explained by differences in study methodology.[2,3]

Different mechanisms contribute to impaired exercise performance under heat stress, including adjustments in cardiovascular, central nervous system, and skeletal muscle function.[1] However, little is known about which factors predispose athletes to the magnitude of performance decrements during exercise in the heat. Hyperthermia was initially suggested to be a critical determinant of exercise performance in the heat,[4,5] but Tatterson et al[6] reported a comparable T_C in athletes performing cycling time trials in normal compared to hot conditions, despite significant performance loss in the hot condition. Similarly, de Korte et al[3] found no association between peak T_C and performance decrements of athletes exercising in hot and humid conditions. Other factors that have previously been linked to performance decrement in the heat are T_{sk}, thermal perception, rate of heat accumulation, and indicators of cardiovascular strain (ie, stroke volume, cardiac output, mean arterial pressure).[7–10] However, previous studies were limited by a small sample size and therefore could only examine few factors, which hampers the integrative assessment of predisposing factors and thus does not reveal the extent to which various factors play a role in limiting performance in the heat.

Therefore, the aim of the present study was to identify factors associated with performance decrements during exercise under hot and humid ambient conditions in a large cohort of elite athletes. All athletes performed a personalized incremental cycling tests in an environmental chamber under temperate conditions and a similar test under hot and humid environmental conditions, while cardiovascular, thermoregulatory, and perceptual responses were measured. The results of this study can help to identify athletes who are prone to performance loss during exercise under heat stress, and thereby implement tailored preparation strategies to optimize performance.

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Methods

Participants

Dutch elite athletes were recruited via TeamNL infrastructures (ie, national sports federations, coaches, embedded scientists). Athletes aged ≥16 years old and practicing an outdoor sport discipline on an international level were eligible to participate in this study. Exclusion criteria were based on the use of the ingestible temperature capsule: (1) body weight < 36.5 kg, (2) presence of an implanted electro-medical device, (3) history of obstructive or inflammatory bowel disease or surgery, or (4) scheduled MRI scan within 5 days of the experiment. All participants gave written informed consent prior to inclusion. The study was carried out in accordance with the Declaration of Helsinki and was approved by Medical Ethical Committee of the Radboud University Medical Center (#2018-4640).

Study Design

The rationale and design of this study have been described previously.[11] In short, athletes were invited to perform 2 personalized incremental exercise tests on a cycling ergometer (Lode ergometer, Lode B.V., or Tacx Neo Smart T2800, Tacx B.V.). The exercise tests were performed in a climate chamber under temperate conditions (TEMP; ambient temperature [$T_{ambient}$] 15.9 °C (1.2 °C), relative humidity (RH) 55% (6%), ambient vapor pressure 0.99 kPa, and absolute humidity 0.0075 kg/m^3) and simulated hot—humid conditions (HOT; $T_{ambient}$ 31.6 °C [1.0 °C], RH 74% [5%], ambient vapor pressure 3.45 kPa, and absolute humidity 0.0245 kg/m^3). Only natural airflow (~0.2 m/s) was present in the climate chamber. The first test was always performed in TEMP, and the exact same individualized exercise protocol was then repeated in HOT. Both exercise tests were separated by ≥48 hours and were performed at the same time of the day (between 08:30 AM and 04:00 PM) to minimize any circadian rhythm effects. Participants were asked to refrain from strenuous exercise (>24 h) and consumption of alcohol or caffeine (>12 h), wear the same clothes for both exercise tests, eat the same diet from the moment of awakening onward, and consuming their last meal ≥3 hours preceding the measurements. Moreover, they were instructed to register their fluid intake on the day of each study visit from the moment they woke up and consume 500 mL of water ~2 hours before arriving at the laboratory. Upon arrival, compliance with these instructions was verified by the research team, ensuring that athletes were euhydrated at the start of the exercise protocol. Participants ingested a temperature capsule (myTemp) ~3 hours prior to both study visits and were not allowed to ingest any fluids during the exercise protocol. Before entering the climate chamber, body height (Road Rod Portable Stadiometer, Hopkins Medical Products) and weight (Seca robusta 813 scale) were measured and measurement equipment for T_C, T_{sk}, and HR were attached.

Personalized Exercise Protocol

After entering the climate chamber, the cycle ergometer was fitted to the participant and the settings were kept the same for both test days. The experimental protocol started with 5 minutes of seated rest, where the last minute was used to determine baseline values. Next, participants started the warm-up phase by cycling at 100 W and were instructed to maintain a cycling cadence of 80 to 100 revolutions per minute throughout the whole protocol. After 3 minutes, the workload was gradually increased to reach 70% of the athlete's maximal heart rate. The workload was then kept equal for the remaining minutes of the warm-up phase. After 20 minutes of warm-up, the workload was increased every 3 minutes by 5% of the workload corresponding to 70% of the maximal HR until volitional exhaustion. Participants were verbally encouraged to give maximal effort. After exercise cessation, participants had a 3-minute active cooldown at a self-selected wattage, followed by 10 minutes of seated rest. A visual overview of the study protocol is presented in Supplementary Material (available online).

Measurements

Exercise Performance

Time to exhaustion (TTE; expressed in minutes) was measured from the start of warm-up until volitional exhaustion. Performance loss was calculated as the difference in TTE between HOT relative to TEMP: Change in exercise performance (%) = (HOT − TEMP)/TEMP × 100.

Core Temperature (T_C)

A validated ingestible telemetric temperature capsule system (myTemp)[12,13] was used to continuously measure T_C at predefined 10-second intervals. Temperature data were wirelessly transmitted to the associated waist-band that was worn at waist level and placed over athlete's sports clothing. Minute averages were calculated after data extraction.

Skin Temperature (T_{sk})

T_{sk} was measured at 20-second intervals using wireless temperature recorders (iButton DS1922L, Dallas Semiconductor Corp). The recorders were attached to the skin at 4 distinct locations (neck, right scapula, left hand, and right shin)[14] using sweat proof Tegaderm film (Tegaderm). Resolution was set at 0.0625 °C. Weighted minute averages were calculated according to international standard operations.[14]

Heart Rate

HR was measured at 1-second intervals using a Polar system (Polar V800, Polar Electro Oy) with chest strap (Polar chest strap H10, Polar Electro Oy), and minute averages were calculated.

Whole Body Sweat Rate

Body weight was measured to the nearest 100 g using an electronic weighting scale (Seca robusta 813 scale). Dehydration rate (%) was calculated as the relative difference between body weight (in shorts and underwear, towel-dried) at baseline and directly after finishing the experimental protocol. WBSR (in liter per hour) was calculated as the difference between body weight at baseline and after finishing, divided by exercise duration.

Perceptual Outcomes

Thermal sensation was assessed using a 7-point scale ranging from cold (−3) to hot (+3),[15] whereas thermal discomfort was assessed using a 4-point scale ranging from comfortable (1) to very uncomfortable (4).[15] Rating of perceived exertion (RPE) was assessed using the 15-point Borg scale, ranging from 6 (very very light) to 20 (maximal exertion).[16] Thermal discomfort, thermal sensation, and RPE were asked at baseline, every 5 minutes during warm-up, and every 3 minutes during the incremental exercise phase.

A portable climate monitoring device (Davis instruments Inc) was used to measure $T_{ambient}$, RH and wet bulb globe temperature. The device was located at table height in the center of the climate chamber. Ambient vapor pressure and absolute humidity were calculated accordingly.

Data Processing

For T_C, T_{sk}, and HR, peak values were determined and resting values were defined as T_C, T_{sk}, and HR in the last minute before the onset of exercise. Exercise-induced increases in T_C, T_{sk}, and HR were defined as the difference between peak values and resting values. In addition, relative differences between HOT and TEMP ([HOT − TEMP]/TEMP × 100%) were calculated for peak T_C, T_{sk}, and HR, for exercise-induced increases in T_C, T_{sk}, and HR, as well as for WBSR and peak RPE.

Statistical Analysis

Statistical analyses were performed using R (Rstudio, version 2023.06.2+561). The level of statistical significance was set at $P < .05$. Normality distribution was checked visually and using Shapiro–Wilk test, and presented as mean (SD) in case of a normal distribution or median [interquartile range] in case of nonparametric distribution or categorical variables, unless indicated otherwise. Paired sample t tests and Wilcoxon Signed-rank tests were used to compare variables in HOT versus TEMP. Univariable linear regression analyses were performed with performance loss (ie, relative difference in TTE between HOT and TEMP) as dependent factor and athlete characteristics (ie, age, sex, BMI, BSA, BSA-to-mass ratio, sport discipline), exercise responses (ie, WBSR, resting HR, peak HR, exercise-induced increases in HR both in HOT and TEMP, dehydration rate), thermoregulatory responses (ie, resting T_C and T_{sk}, peak T_C and T_{sk}, and exercise-induced increases in T_C and T_{sk} both in HOT and TEMP), perceptual outcomes (ie, peak RPE, resting thermal sensation and thermal discomfort, and peak thermal sensation and thermal discomfort both in HOT and TEMP), and variables indicating differences between the HOT and TEMP condition (ie, relative differences between HOT and TEMP for RPE, WBSR, dehydration rate, peak HR, T_C, and T_{sk}, and exercise-induced increases in HR, T_C, and T_{sk}) as independent factors. Thereafter, a multivariable linear regression model was built using forward stepwise entry. Only variables with a P value < .10 in the univariable regression analyses were offered. Before entering, variables were checked for multicollinearity using Pearson correlation coefficients. In case of strong correlations between 2 independent variables ($r > .7$),[17] the variable with the lowest level of significance in the univariable model was excluded. Variables included in the final multivariable model were checked for multicollinearity using the variance inflation factor, with values >5 indicating moderate and values >10 indicating high collinearity.[18]

Results

Participants

A total of 107 elite athletes were included in this study. One participant dropped out due to an ankle injury and was, therefore, excluded from further analyses. The analytical cohort consisted of 106 athletes (26 ± 5 years old, 49% male; Table 1), and none of

them participated in a heat-acclimation program in the months prior to participating in this study. There was some missing data due to technical problems: T_C in 2 participants in TEMP, baseline T_C in 3 participants in HOT, peak T_C in 1 participant in HOT, and baseline T_{sk} and WBSR in 1 participant in HOT.

Exercise Performance

TTE decreased from 60 (14) minutes in TEMP to 44 (10) minutes in HOT, corresponding to a performance decrement of 26% (11%) (Table 2). Performance decrements ranged from 4% to 48% between individuals, while 2 athletes showed performance improvements in HOT (8% and 15%).

Thermoregulatory Responses

Resting T_C was similar in TEMP versus HOT ($P = .28$), while peak T_C and exercise-induced increase in T_C were higher in HOT ($P < .001$; Table 2). Resting T_{sk}, exercise-induced increase in T_{sk}, and peak T_{sk} were higher in HOT versus TEMP (all $P < .001$; Table 2).

Regression Analyses

Univariable regression analyses revealed 21 variables with P values < .1, which were considered for stepwise entry in the multivariable analyses. Seven of these parameters were related to exercise responses, 6 to the magnitude of thermoregulatory responses, 4 to perceptual outcomes, and 4 to athlete characteristics (Figure 1). BSA-to-mass ratio and peak T_{sk} in TEMP were excluded for stepwise entry in the multivariable model due to multicollinearity with BMI and relative difference in T_{sk} between HOT and TEMP, respectively ($r > .7$). The multivariable model (Figure 2) revealed that higher dehydration rates and a higher peak thermal discomfort score in TEMP were significantly associated with greater performance decrements, whereas higher BMI, female sex, greater exercise-induced increases in T_C in HOT, and greater relative differences between HOT and TEMP in peak HR and in exercise-induced increases in HR were significantly associated with smaller performance decrements. Variance inflation factors ranged between 1.2 and 2.1, indicating that collinearity was not an issue between independent variables included in the multivariable model. The full model was able to explain 58% of the variability in performance loss (adj $R^2 = .58$; $P < .001$).

Discussion

The aim of this study was to identify factors that are associated with performance decrements during exercise under hot and humid ambient conditions. Our study revealed that higher levels of performance loss during exercise in hot–humid conditions were associated with higher dehydration rates and more thermal discomfort in TEMP. On the other hand, lower levels of performance decrements were associated with a higher BMI, female sex, greater exercise-induced increases in T_C in HOT, as well as a higher peak HR and exercise-induced increase in HR in HOT versus TEMP. These factors could jointly explain 58% of the variability in performance decrements across athletes. This information can help athletes and coaches to identify athletes who are more prone to greater levels of performance loss during exercise under heat stress, enabling them to tailor preparation strategies that account for individual physiological responses and thereby optimize performance.

Table 1   Athlete Characteristics of the Analytical Cohort

	All athletes (N = 106)	Males (n = 52)	Females (n = 54)
Age, y	26 (5)	26 (5)	26 (5)
Height, cm	180 (12)	188 (10)	172 (7)
Weight, kg	76.1 (13.9)	83.9 (13.0)	68.5 (10)
BSA, m^2	1.95 (0.23)	2.10 (0.20)	1.81 (0.15)
BMI, kg/m^2	23.4 (2.7)	23.8 (2.7)	23.1 (2.6)
BSA/mass, m^2/kg	0.0259 (0.0019)	0.0252 (0.0016)	0.0266 (0.0018)
Sport discipline, n (%)			
Endurance	27 (26%)	12 (23%)	15 (28%)
Mixed	31 (29%)	22 (42%)	9 (17%)
Power	12 (11%)	7 (14%)	5 (9%)
Skill	36 (34%)	11 (21%)	25 (46%)

Abbreviations: BMI, body mass index; BSA, body surface area.

Table 2   Exercise Responses, Thermoregulatory Responses, and Perceptual Outcomes in the Temperate Versus Hot–Humid Condition, and Relative Differences Between Conditions

	Temperate condition	Hot–humid condition	P	Relative difference, %
Exercise responses				
Time to exhaustion, min	60 (14)	44 (10)	<.001	−25.9 (10.7)
Peak power output, W	228 (63)	191 (53)	<.001	−15.7 (7.2)
Peak power output, W/kg	3.1 (0.9)	2.6 (0.8)	<.001	−15.7 (7.2)
Resting HR, bpm	74 (12)	82 (14)	<.001	10.8 (16.4)
Peak HR, bpm	179 (12)	182 (11)	<.001	2.1 (4.3)
Exercise-induced increase in HR, bpm	105 (13)	101 (15)	.008	−2.7 (15.0)
WBSR, L/h	0.8 (0.3)	1.4 (0.6)	<.001	77.3 (119.0)
Dehydration rate, %	1.1 (0.4)	1.3 (0.5)	<.001	31.0 (92.2)
Weight preexercise, kg	76.1 (13.9)	76.0 (13.8)	.58	0.0 (1.1)
Weight postexercise, kg	75.2 (13.8)	74.9 (13.7)	.03	−0.3 (1.2)
Thermoregulatory responses				
Resting T_C, °C	37.1 (0.4)	37.1 (0.4)	.28	−0.1 (1.1)
Peak T_C, °C	38.7 (0.4)	38.9 (0.6)	<.001	0.6 (1.2)
Exercise-induced increase in T_C, °C	1.5 (0.4)	1.8 (0.6)	<.001	24.1 (46.1)
Resting T_{sk}, °C	30.5 (0.7)	33.6 (0.7)	<.001	10.2 (2.9)
Peak T_{sk}, °C	32.3 (1.1)	36.7 (0.6)	<.001	14.0 (3.4)
Exercise-induced increase in T_{sk}, °C	1.7 (1.0)	3.1 (0.9)	<.001	118 (1140)
Perceptual outcomes				
Peak RPE, au	20 [14, 20]	20 [12, 20]	.14	−0.9 (6.9)
Resting thermal sensation, au	−2 [−3, 1]	1 [0, 3]	<.001	
Peak thermal sensation, au	3 [0, 3]	3 [2, 3]	<.001	
Resting thermal discomfort, au	2 [1, 4]	1 [1, 3]	<.001	
Peak thermal discomfort, au	4 [1, 4]	4 [2, 4]	<.001	

Abbreviations: bpm, beats/min; HR, heart rate; RPE, rate of perceived exertion; T_C, core temperature; T_{sk}, skin temperature; WBSR, whole body sweat rate. Note: Data are presented as mean (SD) or median [1st quartile, 3rd quartile].

Exercise performance decreased by 26% (11%) (16 [8] min) in HOT, with large interindividual differences in performance decrements up to a 48% lower TTE compared to TEMP. This is in line with previous studies investigating the impact of heat stress on exercise performance, including a review article reporting average performance reductions for TTE tests ranging from 12% to 39%.[2] Our study showed that several factors were associated with higher levels of performance loss during exercise in hot–humid conditions, among which a higher dehydration rate in TEMP was the largest contributor to the model (see Figure 2). This is in line with previous research indicating that dehydration has been found to impair exercise performance,[19] although primarily reported to be detrimental during exercise in hot environments.[20] It could be possible that dehydration rate in HOT was masked by other exercise-induced responses, such as

A

Beta coefficients for continuous variables

B

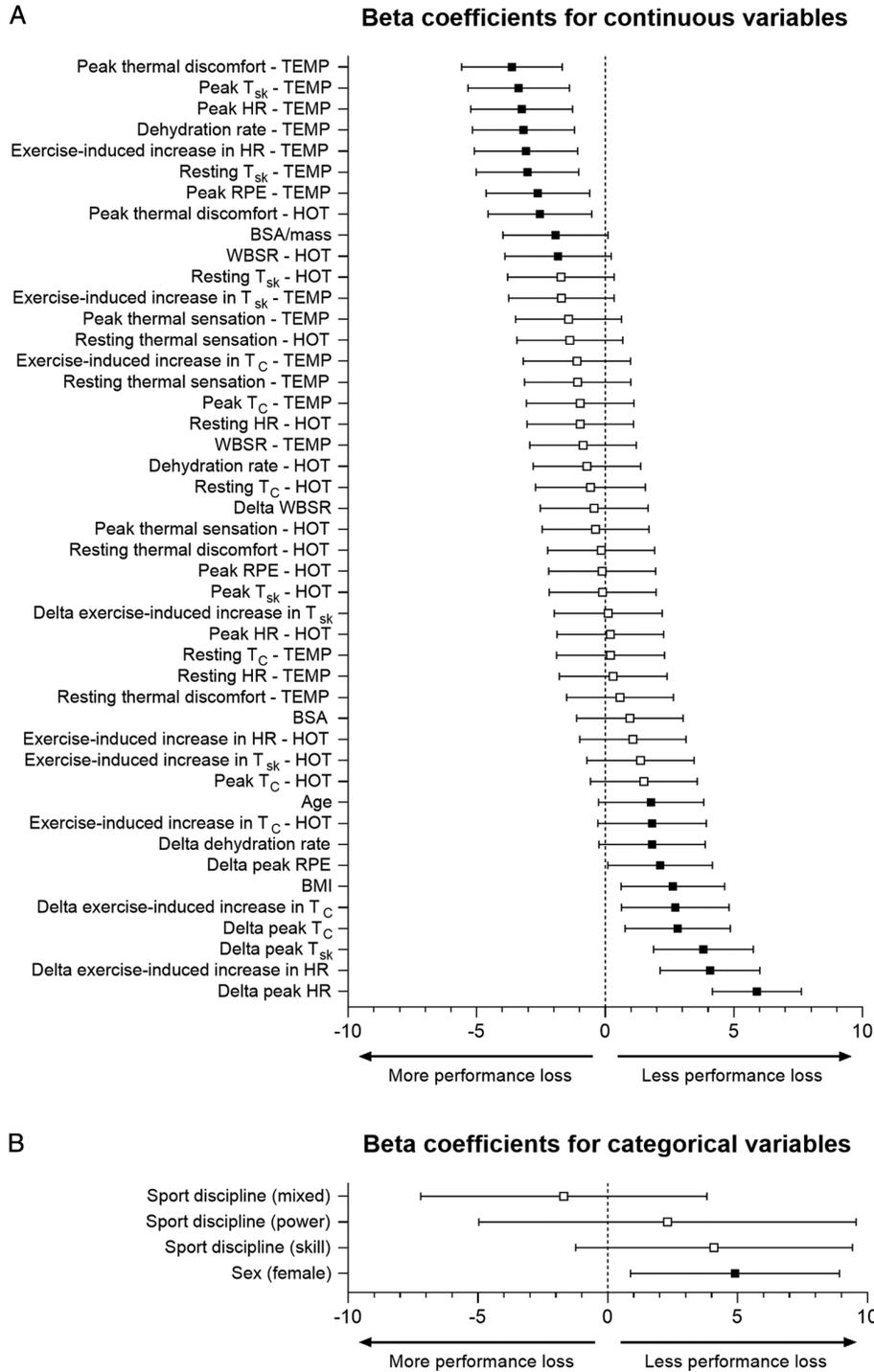**Beta coefficients for categorical variables**

Figure 1 — Beta coefficients with 95% CIs from all univariable linear regressions with performance loss including continuous (A) and categorical (B) variables. For the categorical variables, endurance is the reference category of sport discipline, while male is the reference category for sex. Variables with negative beta coefficients indicate that an increase in the variable is associated with more performance loss, while variables with positive beta coefficients indicate that an increase in the variable is associated with less performance loss. TEMP and HOT indicate variables measured in the temperate or hot—humid condition, respectively. Delta indicates the relative difference between HOT and TEMP. Black squares indicate variables with $P < .10$ and thus are considered for stepwise entry in the multivariable model. BSA indicates body surface area; HR, heart rate; RPE, rate of perceived exertion; T_C, core temperature; T_{sk}, skin temperature; WBSR, whole body sweat rate.

increases in HR, T_C, and T_{sk}, making it less discriminative compared to the TEMP condition. Furthermore, the observation that dehydration rate during TEMP was a strong contributor to our model offers important possibilities for testing athletes for their heat vulnerability

and to develop a proper hydration strategy to replenish fluid loss and prevent large performance decrements.[21]

Additionally, we found that experiencing greater thermal discomfort during exercise in TEMP was associated with more
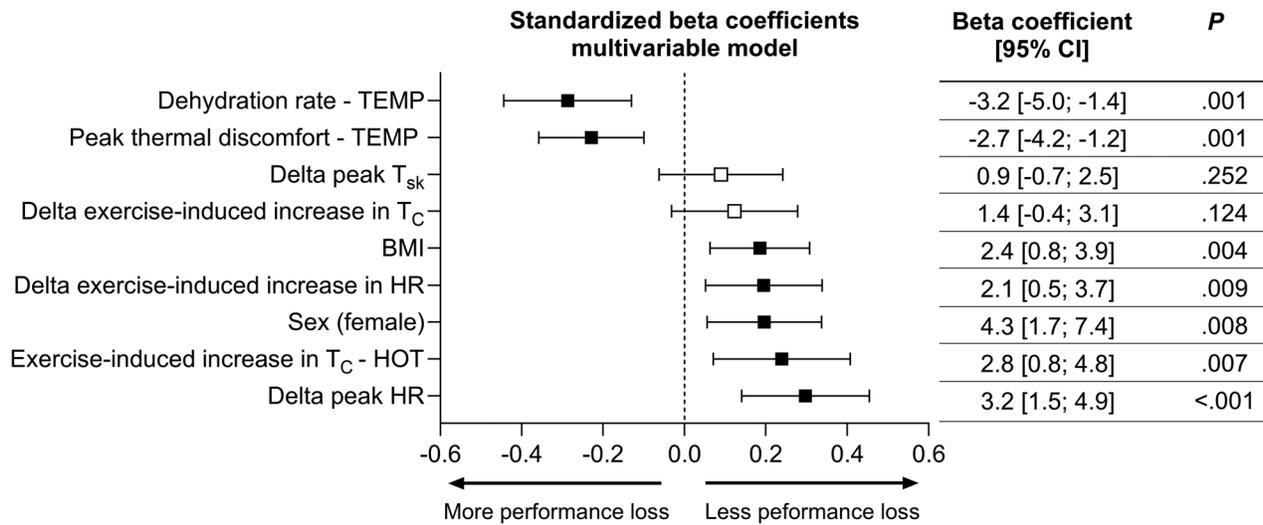
Figure 2 — Forest plot showing standardized beta coefficients with 95% CIs of factors included in the multivariable model for performance loss. On the right, corresponding beta coefficients, 95% CI, and *P* values are presented. TEMP and HOT indicate variables measured in the temperate or hot–humid condition, respectively. Delta indicates the relative difference between HOT and TEMP. Black squares indicate variables with $P < .05$. BMI indicates body mass index; HR, heart rate; T_C, core temperature; T_{sk}, skin temperature.

performance loss during exercise in the heat. A possible explanation might be that athletes who already perceive greater thermal discomfort in temperate conditions are more likely to experience even more discomfort in hot conditions, which could not be captured in the score due to a ceiling effect, but this may limit exercise performance sooner compared to athletes perceiving less discomfort. Cooling strategies such as facial cooling or ice towels across neck and shoulders are efficient ways to directly improve thermal comfort,[22,23] whereas heat acclimation has also been shown to enhance thermal comfort,[24] making it a valuable approach to reduce performance loss in the heat.

Our study also identified 5 factors that were significantly associated with lower levels of performance loss during exercise in the heat. First, we found that athletes reaching a higher peak HR in HOT relative to TEMP showed less performance decrements, which was the strongest contributor to the model. This was further reinforced by the observation that a higher exercise-induced increase in HR in HOT relative to TEMP was associated with less performance decrements. These collective findings support the idea that cardiovascular strain is an important determinant for exercise performance in the heat.[6,8] During exercise in the heat, a greater redistribution of blood toward the skin surface occurs to stimulate heat loss. This is detrimental for cardiac filling and stroke volume, and HR for any given workload should be higher in order to preserve cardiac output.[25] Thus, our findings indicate that a greater ability to maximally increase HR in hot–humid conditions is related to less performance decrements, suggesting that these individuals may have a greater tolerance to cardiovascular drift.

Moreover, reaching a higher exercise-induced increase in T_C in HOT was associated with less performance decrements in the heat. Athletes who can tolerate greater increases in T_C before exercise cessation will concurrently experience less performance loss during exercise in the heat. This further highlights the importance of heat acclimation or acclimatization to prepare athletes for exercise in hot–humid environments. Heat acclimation/acclimatization lowers resting T_C while enhancing thermal tolerance,[25,26] which allows athletes for greater exercise-induced increases in T_C and thereby preservation of performance capacity.

We also found an association between sex and performance decrements in the heat, with females experiencing less performance decrements compared to males. Previous studies already reported sex differences in thermoregulation, including females having a higher density of activated sweat glands during exercise.[27] This could stimulate heat loss via evaporation, thereby limiting the exercise-induced increase in T_C. However, sex differences in thermoregulation typically disappear after matching for body size, fitness-level, and acclimation state,[28,29] suggesting that these factors might play an important role as well. Unfortunately, this information was not collected within our study, so we were unable to take those factors into account in our model. Moreover, a higher BMI was found to be associated with less performance decrements in the heat. Little is known about the specific impact of BMI on heat-related performance decrements, so future studies are warranted to explore the impact of body composition on exercise performance under heat stress.

A strength of this study is that we included a unique and large sample of elite athletes. This gave us comprehensive insights in physiological responses during exercise performance in the heat and thereby allowed us to identify multiple factors independently associated with performance decrements. Interestingly, our model explained 58% of the variability in performance decrements across athletes, which is notably high for a physiological model.[30] A limitation of this study is that we did not use a randomized design, as participants always performed the exercise test in TEMP first. This could have resulted in a learning effect, thereby underestimating performance decrements during exercise in the heat and underestimating the impact of factors influencing these performance decrements. Although we considered performing a familiarization trial, this was strongly discouraged by representatives of TeamNL and sport federations due to the busy training schedule of elite athletes and the nonfeasibility to perform multiple exercise tests within a short period. Another limitation of this study is that exercise tests were not sport-specific with limited air flow, which could limit the translation of exercise performance to field setting for athletes. Moreover, athletes were not allowed to drink during the exercise protocol, which is different compared to exercising in

real-world situations and could have accelerated hypohydration and thermal discomfort, potentially further limiting performance.

Practical Applications

The findings of this study could assist coaches to identify athletes who are prone to higher levels of performance loss by monitoring dehydration rates and thermal perception during exercise tests embedded in their training schedules. A combination of such observations with information about the physiological responses during exercise under heat stress could be useful to develop and evaluate tailored heat mitigation strategies in order to optimize performance for targeted events, such as the Los Angeles 2028 Olympic Games.[31]

Conclusions

We found that higher dehydration rates and more thermal discomfort in TEMP were significantly associated with more performance decrements during exercise in hot–humid conditions, while higher BMI, female sex, greater exercise-induced increases in T_C in HOT, and greater relative differences between HOT and TEMP in peak HR and in exercise-induced increases in HR were significantly associated with less performance decrements in the heat. These factors jointly explained 58% of the variability in performance loss across athletes.

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