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Risk factors and predictors of hypothermia and dropouts during open water swimming competitions

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Keywords:	exercise physiology, sport physiology, body composition

Dear editors, Dear reviewers,

Please find attached an amended version of the manuscript of our work previously IJSPP.2020-0875 entitled: “Core temperature decreases down to 32.4 in elite open water swimmers: incidence for performance and risk factors for hypothermia” (and now “Risk factors and predictors of hypothermia during open water swimming competitions”) which we hope you will consider for publication in your journal.

We would like to thank the reviewers and editors for their time spent on reviewing our manuscript. Their very valuable comments and suggestions have significantly helped us improve our work.

As suggested, the authors made a major modification by removing the only non-finisher swimmer from the nH group and correcting the statistical analyses with the new study sample. In addition, they significantly modified the abstract to emphasize the suggestion, especially regarding the effect of experience on $T_{core.}$

Below, we address all of the comments point-by-point, outlining the subsequent modifications, where appropriate:

- **bold quotes: reviewers’ comments**
- quotes: response to the reviewer
- *italic quote: changes in the revised manuscript (L. for line number in the manuscript)*

Reviewer 1

P4 line 40: please consider another word for “worse performance” This phrase is awkward in English – consider “main causes of dropout or poor performance in OWS”

JD: Thank you for this suggestion, the authors have added the suggested content to the manuscript

L43: Hypothermia has been reported as one of the main causes of dropout or poor performance in OWS[6]

P4 line 42 : I believe the medical term is SIPE: Swimming induced pulmonary edema.

JD: Thank you for the correction, the authors have added the suggested content to the manuscript

L44: …and are caused by swimming induced pulmonary edema (SIPE)…

P5 line 62: FINA also has a marathon series with races up to 57 k (river race in South America) etc. However 25k is the upper distance limit at the FINA World Championships. Please correct that it is the longest FINA race at the World Championships. FINA has longer races in our Marathon series.

JD: Thank you for the correction, the authors have added the suggested content to the manuscript

L58: As 25 km is the longest and therefore slowest FINA race at the World Championships [13]…

P4 lines 84-5: I assume the relevance of swallowing disorders, transit disorders or scheduled MRI in 48h is related to the ingested temperature pill. For clarity for readers who are unaware, please consider prefacing with the phrase. No participants had contraindications to the ingestible temperature sensor including swallowing disorders, transit disorders, or scheduled MRI within 48 hours post event..

JD: The authors have added the suggested content to the manuscript

L81: No participants had contraindications to the ingestible temperature sensor including swallowing disorders, transit disorders, or scheduled MRI within 48 hours post event.

P4 line94: please define what you mean by "authorized supplies". In Fina language, we call it "feeding" with required fluid replacement and CHO, electrolytes.

JD: The authors have made the suggested correction to the manuscript.

L91: The 25-km race consisted of 10 laps over a 2500 m course with feeding every 1250 m

P7lines 101-2: Please consider the english in the sentence "Hypothermia-related dropouts were medical diagnostics based on the complaints and symptoms of the nonfinishers." I don't believe you have completed the verb "were"… were ? provided a medical assessment and treatment…..

JD: In this sentence, the authors wanted to define the hypothermia-related dropouts as medical diagnosis based on symptoms and treatment. To clarify, the authors propose to change the sentence as follow:

L97 Hypothermia-related dropouts were defined as the nonfinishers that were medically diagnosed with hypothermia related symptoms and were provided a medical assessment and treatment.

P8line 129 delimiting is not an English word. I believe you mean "delineating"

JD: The authors have made the suggested correction to the manuscript

L127: I-buttons (iButton® Maxim Integrated) were attached to the buoys delineating the course of the event

P9line169 Please consider an English revision. The term "Swimmer taken over by emergency services" is awkward. Perhaps "Swimmer was treated by emergency services."

JD: The authors have added the suggested content to the manuscript

L168: with the lowest T_{core} reached during the race being 32.4°C in a swimmer who was treated by emergency care services.

P10 line186-7: do you mean "Who had previously participated in a 25k race… and who had not previously participated? The word "previously" is important to include for ease of understanding.

JD: The authors have added the suggested content to the manuscript

L186-7 The swimmers who had previously participated in a 25-km race also showed a lower drop than the swimmers who had not previously participated in a 25-km race (-0.41 ±0.89°C vs. -1.78 ±1.40°C, p= 0.018).

P10 line 190: the phrase "the best model was significant"…. Is unclear. What do you mean by this? (also line 220) Do you mean the best regression model?

JD: The authors have added the suggested content to the manuscript, and they defined the model (with equation when applicable). The ANCOVA analysis was also checked using a multiple linear regression analysis (with the exact same results), and the authors kept the multiple linear regression statistic as the emphasis was on the dependent outcome variable (T_{core}). Also, we removed the Figure 2, because both models were described in the text. If suggested, the authors might add a graphical representation for both multiple linear regression (T_{core}) and logistic regression (dropouts) analyses.

L188: After including covariates with p<0.1 in univariate analysis (gender, muscle mass, fat mass and previous participation), the multiple linear regression analysis indicated that the *model including fat-mass and previous participation provided the best fit for predicting* T_{core} *(effect of model:* $F(2,18)=4.95$*,* $p=0.019$*,* $T_{core}= -2.99 + 8.01*\%fat\text{-}mass +0.99*experience[no=0,yes=1]$*,* $R=0.60$*), with the respective effects of the covariates %fat-mass (*$\beta= 3.77$*,* $p= 0.075$*) and previous participation (*$\beta= 3.57$*,* $p= 0.075$*).*

L225 : The best regression model was found after inclusion of the covariates %fat-mass and initial Tcore (effect of model: G^2*:17.255, df: 2,* $p<0.001$*, log odds(H/nH)= 423.18 - 53.86*%fat-mass - 11.11*initial Tcore, overall prediction 90.5%), with the respective effects of the covariates %fat-mass (*$p=0.043$*) and initial Tcore (*$p=0.056$*) (Figure 2).*

P11 line 203: instead of "null" i think you mean "nil". (= zero)

JD: The authors have made the suggested correction to the manuscript

L204: and nil in swimmers who had already participated in a 25-km race

P12 line 288 the word "Cautious" should be "caution" and followed with a ","

JD: The authors have made the correction content to the manuscript

L309: These results should be interpreted with caution,…

Reviewer 2

Major Revisions or Comments

1. The title, with its inclusion of a specific core temperature, read quite awkwardly at present and makes it appear as if it is a case study. I would suggest simplifying the title was something along the lines of "Risk factors and predictors of hypothermia during open water swimming competitions."

JD: Thank you for the suggestion, the authors have added the suggested content to the manuscript

Title: Risk factors and predictors of hypothermia and dropouts during open water swimming competitions

2. Abstract. It seems strange to specifically state that you will be comparing the hypothermia with the non-hypothermia dropout group in the abstract, yet provide no information about it and the rest of the abstract?

JD: Based on this comment and the following comments, and as suggested, the authors provided a revision of the entire manuscript with removing the nH nonfinisher (n=1) and revised all the analysis with the new results (n=21).

L12: Hypothermia-related dropouts (H group) were compared to finishers (nH group).

3. Not absolutely required, but it might be relevant to confirm/cite whether the telemetric pills are valid for individuals who are underage or potentially of smaller body size.

Thank you for this comment, as suggested the authors cited a reference about the use of the telemetric pill in young adolescents.

L118: This system has previously been used to monitor elite athletes in official competitions performed in hot[16] and cold environments[4], and has also been used to monitor T_{core} in young adolescents[17].

4. The methods have minimal information on how you are quantifying speed changes or speed variance. As this is one of your main parameters, I would suggest providing much more detailed information on how this is being quantified.

JD: As suggested, the authors added some information about the quantification of speed changes. Also, we added a sentence in the limitation section

L 130: Speed. The speed was calculated as an average speed on each lap using the official lap time.

L315 Also, the speed was calculated as the average speed on each lap, and not by monitoring the continuous speed changes, but the repeated correlation analysis was based on the association between the changes in speed and temperature over each lap. Further research on the association between speed and T_{core} might use GPS devices for stroke count quantification and swimming velocity.

5. There is also minimal information on how the comparisons between groups are being made. For example, from the methods it is not clear whether the nH and the finisher are being put together as one main group or whether they are being analysed separately.

JD: As suggested, the authors provided a revision of the entire manuscript and revised analysis with removing the nH nonfinisher (n=1)

6. I am also unclear on the rationale for analysing the nonfinisher (non-hypothermic) at all? It might be relevant if that one participant completed 20+ kilometres? If you are going to include that individual, it would be good to provide some more context such as the distance completed.

JD: As suggested, the authors provided a revision of the entire manuscript and revised analysis with removing the nH nonfinisher (n=1) from the nH group and from the analysis

L78: and one participant dropped out because of muscle pain before mid-race.

7. Line 158. It is only reaching here that I'm now understanding that the nH group represents finishers and the nonfinisher (non-hypothermic). It is likely that other readers will be as equally confused as I was, so I would recommend that you go through the first part of the manuscript to make this much clearer.

JD: As suggested, the authors provided a revision of the entire manuscript and revised analysis with removing the nH nonfinisher (n=1) from the nH group and from the analysis

8. Consider adding more context about what rewarming facilities were available for both finishers and the H group.

As suggested, we provided this information and added the following sentence:

L101 For all participants, rewarming facilities on the site were heated baths, access to a place of shelter with showers, dry towels and/or blankets, warm beverages and food/fruits

9. Line 188-192. Is there an actual regression equation being presented here? Is it in a figure or table? All I'm seeing is that the model is significant but no information on the model itself?

JD: The authors have added the suggested content to the manuscript

L188: After including covariables with $p<0.1$ (gender, muscle mass, fat mass and previous participation) with backward stepwise selection were conducted, the ANCOVA model was significant ($F= 6.82$, $p= 0.019$)

L225 : The best regression model was found after inclusion of the covariates %fat-mass and initial Tcore (effect of model: G^2:17.255, df: 2, $p<0.001$, log odds(H/nH)= 423.18 - 53.86%fat-mass - 11.11*initial Tcore, overall prediction 90.5%), with the respective effects of the covariates %fat-mass ($p=0.043$) and initial Tcore ($p=0.056$) (Figure 2).*

10. Line 250. Definition of "elite." Considering that more than half of the individuals have not previously participated in a 25 km race and also that half of the participants were at or under 18 years old, I'm wondering whether the term "elite" is actually appropriate?

JD: The authors have removed the suggested content to the manuscript. The participants were high-level OW swimmers at a national or international level but half where novice for the 25-

km race. Thus, the authors included the term “competitive race” and “national or international level” swimmers instead of “elite” swimmers

11. To this reviewer, it seems absolutely striking that the dominant predictor for hypothermia is actually being younger (all being 18 or younger) and also inexperience with the 25 km race (all were first-timers). In light of this, I would encourage the authors to perform a separate analysis based on age (18 or younger versus >18) and also experience (first timers versus veterans). For example, are the younger competitors also those with generally less body fat or slower swing speeds? This set of analyses would appear critical in terms of developing health and safety policies. For example, it might be relevant to consider minimal ages for entry into such events and/or increased education for first-time competitors.

Thank you for this very valuable comment. In the initial version of the manuscript the authors thought that the multiple logistic regression would be sufficient to adjust the predicting model for confounding. As suggested, we specifically tested the variables for potential confounders (among the significant covariables). These analyses highlighted that younger individuals had lower fat-mass and greater muscle mass, but no statistical differences were found according to experience. We made the change in the manuscript as follow:

L217 “To analyze potential confounders, we tested the effect of age (≤18 versus >18 years) and experience (first timers versus experienced swimmers) on the dependent co-variables. Swimmers ≤18 years had lower %fat mass (13.0 ±5.6% vs. 20.9 ±4.9%, t= -3.42, p= 0.003) and had greater %muscle mass (43.1 ±6.3% vs. 37.2 ±3.1%, t= 2.70, p= 0.014). No significant association or difference were found for covariables/cofactors according to experience.”

12. I would also like to see specific discussion around the age and the experience factors within the discussion.

JD: Thank you for this very pertinent comment. As suggested, we added a specific discussion on the experience within the Discussion section.

L280: Also, the participants who never participated in a 25-km race had greater a T_{core} drop and had greater rates of hypothermia-related dropouts. Higher rates of dropout in novice (vs. experienced) athletes, influenced by psychosocial factors, had previously been described in ultra-trailers, suggesting the importance of preparation and self-efficacy based on past experiences [27]. In OWS, these psychosocial factors should be considered in addition with anthropometric and physiological factors since novice are often the younger participants with low fat mass. These results should draw the attention of professionals on the need to properly prepare novice swimmers for this race and the risk of hypothermia.

13. In the discussion, I think it is also important to highlight that this particular competition was at the absolute lowest limit where wetsuits are still banned. This may lead to an important conversation about whether threshold temperatures for wetsuit use may need to be revisited or altered.

JD: Thank you for this very pertinent comment. As suggested, we added that this particular competition was at the lowest limit where wetsuits are still banned, in the discussion part. Also, we added a comment in the practical application section. Finally, we added this point in the Conclusion section of the Abstract

Abstract: L24: Conclusion: During a OW 25-km competition at 20-21°C,

L255Our results showed that during a 25-km competition at the absolute lowest limit where wetsuits are still banned (20-20.5°C), OW swimmers are exposed to T_{core} drop and hypothermia and confirmed that hypothermia is a common condition in OWS[6,11,19]

L 331: Finally, our results raise the question of adapting the actual wetsuits guidelines for open water competitions, especially in swimmers at higher risk (e.g., minimal water temperature or type of wetsuit for junior male swimmers).

14. From figure 1, it appears that at least four of the nH group reached core temperature is at least as low as those in the H group. Is it possible to go back through the data and see what may be unique about these four individuals that allowed them to "survive?" I believe that it is also relevant to mention this fact in either the results or the discussion, namely that it is possible to have low temperatures and yet still complete the event.

JD: Thank you for this very specific and pertinent comment. After analysis of the curve and data, 2 swimmers (ID 11 and ID12) who had low T_{core} at 2500 (below 36.0°C) similar to the Ts of the H group and those swimmers increased their speeds during the lap 2500-5000m (for ID 12) and 5000-7500m (ID 11). As a consequence, T_{core} remain stable or increased, which could allow them to finish the race. Also both swimmers were international level swimmers with previous participation in 25km race or longer events, and experience might have enhanced their ability to manage/cope with low T_{core}. We added the content in the manuscript as follow:

L288: Among the finishers, 2 swimmers had low T_{core} at 2500m (below 36.0°C), but they could increase their speeds during the lap 2500-5000m and 5000-7500m and their T_{core} remained stable or increased so they were able to finish the race. Also, the 2 swimmers were international level swimmers with previous participation in 25km race and/or longer events, and experience might have enhanced their ability to manage/cope with low T_{core}.

15. Abstract page, line 13. "(incl. x nonfinishers…" Should X be replaced by an actual number? Same with line 100/101.

JD: This sentence have been removed since the nH group was only made of finishers.

16. Lines 185/186. Consider changing "swimmer" to "swimmers." Swimmer makes it read as if only one swimmer was in each group.

JD: The authors have corrected the suggested content to the manuscript

L185: The swimmers who had previously participated in a 25-km race also showed a lower drop than the swimmers who had not previously participated in a 25-km race (-0.41 ±0.89°C vs. -1.78 ±1.40°C, p= 0.018).

17. Line 251 delete one of the "is as"

JD: The authors have deleted the suggested content in the manuscript

255: Our results showed that during a 25-km competition at the absolute lowest limit where wetsuits are still banned (20-20.5°C), OW swimmers are exposed to T_{core} drop and hypothermia and confirmed that hypothermia is a common condition in OWS[6,11,19]

18. Line 265. Change oldest to "older"

JD: The authors have corrected the suggested content to the manuscript

Risk factors and predictors of hypothermia and dropouts during open water swimming competitions

ABSTRACT

Purpose: To measure the core temperature (T_{core}) in open-water (OW) swimmers during a 25-km competition and identify the predictors of T_{core} drop and hypothermia-related dropouts.

Methods: 24 national and international level OW swimmers participated in the study. Participants completed a personal questionnaire and a body fat / muscle mass assessment before the race. The race consisted in 10 laps over a 2500 m course and speed was calculated as an average speed on each lap. T_{core} was continuously recorded via an ingestible temperature sensor (e-Celsius, BodyCap). Hypothermia-related dropouts (H group) were compared to finishers (nH group).

Results: Average pre-race T_{core} was 37.5 ±0.3°C (n= 21). 7 participants dropped out due to hypothermia (H, n= 7) with a mean T_{core} at dropout of 35.3 ±1.5°C. Multiple logistic regression analysis found that body fat percentage and initial T_{core} were associated with hypothermia- (G^2:17.26, p<0.001). Early T_{core} drop ≤37.1°C at 2500m was associated with a greater rate of hypothermia-related dropouts (71.4% vs. 14.3%, p= 0.017). Multiple linear regression found that body fat percentage and previous participation were associated with T_{core} drop (F= 4.95, p= 0.019). There was a positive correlation between the decrease in speed and T_{core} drop (r= 0.462, p <0.001).

Conclusion: During a OW 25-km competition at 20-21°C, lower initial T_{core} and lower body fat as well as premature T_{core} drop were associated with an increased risk of hypothermia-related

dropout. Lower body fat and no previous participation as well as decrease in swimming speed were associated with T_{core} drop.

INTRODUCTION

Open-water swimming (OWS) characterizes any swimming competition in rivers, lakes, oceans or water channels. The 25-km OWS requires ~5 hours of swimming, during which swimmers must cope with various environmental and physiological parameters (water temperature, race strategies, etc.) that may lead to changes in their body temperature [1,2]. The maintenance of core temperature (T_{core}) while swimming depends on the balance between heat production (related to exercise intensity) and dissipation. However, heat dissipation mechanisms during swimming differ from land sports, as water has a high specific heat and greater conductivity than air, increasing conductive and convective transfer[3]. Thus, unlike other sports in cold air, in which T_{core} increases despite air temperature down to ~0°C[4], swimming in cold water usually results in excessive thermolysis, which may not be compensated by metabolic heat production, leading to a decrease in T_{core}[2].

Hypothermia is broadly defined as an unintentional fall in T_{core} below 35°C and can be classified as mild (T_{core} 32.2-35°C), moderate (32.2-28°C), or severe (<28°C)[5]. Hypothermia has been reported as one of the main causes of dropout or poor performance in OWS[6]. In addition, more than 70% of the deaths in triathlons occur during the swimming phase and are caused by swimming induced pulmonary edema (SIPE) and cardiac arrythmias, most frequently in cold water[2,7]. Of note, fatal events are more frequent during competitions than during leisure or training swims, and it has been hypothesized that an "autonomic conflict" with the coactivation of the sympathetic and parasympathetic drive during cold-water swimming could be worsened by anger-induced sympathetic arousal during competition or mass events[2,8].

To reduce the risk of hypothermia in swimmers, the Fédération Internationale de Natation's (FINA) enacted rules stipulating that water temperature should be at minimum 16°C, and that wetsuits are compulsory when water temperature is <18°C and are allowed when water temperature is <20°C[9]. In addition to environmental factors, hypothermia in athletes may also depend on intrinsic parameters (e.g., sex, age, weight, body composition)[10]. However, few studies have tested elite athletes during competitions[11,12] and the risk factors associated with a decrease in T_{core} and hypothermia-related dropouts during a competitive event remain unknown.

As 25 km is the longest and therefore slowest FINA race at the World Championships [13], it may represent a particular hypothermic challenge to swimmers. Thus, the objectives of the current study were to continuously monitor T_{core} in swimmers during a 25-km race and to identify the potential predictors of T_{core} drop and hypothermia-related dropouts. We hypothesized that OW swimmers are exposed to T_{core} drop during a 25-km competition and that individual parameters (youngest swimmers, male) and/or body composition (low fat mass) could be predictors of T_{core} drop and dropouts.

METHODS

The protocol was validated by the Committee for the Protection of Persons (CPP Sud Méditerranée I Marseille, number 2019-A00542-55 1939) and was registered in an international database (ClinicalTrials.gov NCT04460339). The study was conducted in accordance with the Declaration of Helsinki, and written consent was obtained from all participants, as well as their legal representatives when applicable (i.e., parents for underage participants).

Subjects

Twenty-four (12 males, 12 females; age range 15-32 years old; 6 underage) of the 39 competitors of the 25-km national Open-Water Championship (France, 2019) volunteered for this study. However, one participant did not start due to a muscle-tendinous injury, one participant had incomplete data and one participant dropped out because of muscle pain before mid-race. The characteristics of the 21 remaining participants are presented in Table 1. Ten swimmers were international-level swimmers, and 3 were medalists in international FINA championships. No participants had contraindications to the ingestible temperature sensor including swallowing disorders, transit disorders, or scheduled MRI within 48 hours post event.

Design

Participants completed a personal questionnaire and a body composition assessment the day before the event. They were given an ingestible temperature sensor (e-Celsius®, BodyCap®, Caen, France) with the instructions to swallow it immediately before going to bed, the night before the race. All sensors were checked on the day of the 25-km event, and if the sensor could not be detected, the participant had to swallow another sensor immediately (in five swimmers).

The 25-km race consisted of 10 laps over a 2500 m course with feeding every 1250 m. No instruction was given to the swimmers participating in our study concerning the management of their race. The water temperature was between 20.2°C and 21.0°C during the race, and the use of wetsuits was prohibited. For the nonfinishers, the time of abandonment, mileage swum and cause of abandonment were obtained from the organizing staff (or medical staff if needed), and nonfinishers were also asked about the cause of dropouts and the perception of cold. Hypothermia-related dropouts (H group) were compared to finishers (nH group). Hypothermia-related dropouts were defined as the nonfinishers that were medically diagnosed with hypothermia related symptoms and were provided a medical assessment and treatment. For the other participants, the performance (time) and the final classification on the 25-km race were collected. For all participants, rewarming facilities on the site were heated baths, access to a place of shelter with showers, dry towels and/or blankets, warm beverages and food/fruits

Methodology

Prerace questionnaire. The data collected were sex, age, level of competition, best performance, average number of training sessions per week and total swimming distance per week.

Body composition. Fat mass (in kg, index and % of body mass), fat-free mass (in kg, index and % of body mass) and muscle mass (total, trunk and upper-lower limbs) were estimated using bioelectrical impedance analysis (mBCA 525, Seca, Germany). Body muscle-to-fat ratio was calculated as total muscle mass: fat mass. Measurements were performed in the supine position using eight electrodes on both sides with the subject lying on a nonconductive surface[14]. Adhesive gel electrodes (Kendall, H59P, Covidien IIc, Mansfield, MA, USA) were placed at defined anatomical sites on the dorsal surfaces of the hand, wrist, ankle and foot according to the manufacturer's instructions.

Core temperature. Gastrointestinal temperature was monitored using an ingestible electronic sensor (e-Celsius, BodyCap, Caen, France) that provides a continuous, reliable and validated measurement of T_{core} [15]. This system has previously been used to monitor elite athletes in official competitions performed in hot[16] and cold environments[4], and has also been used to monitor T_{core} in young adolescents[17]. Temperature was monitored every 30 s with the data being stored within the ingestible sensor and downloaded to an external receiver after the race (e-Viewer®, BodyCap, Caen, France).

Perceptual responses. Immediately at the end of the race, participants' perception of cold was assessed using the Cold Discomfort Scale (CDS), which is a reliable and valid subjective judgment scale for the assessment of patient thermal state in a cold environment and ranges from 0 (no perception of cold) to 10 (maximum feeling of cold)[18].

Water temperature. I-buttons (iButton® Maxim Integrated) were attached to the buoys delineating the course of the event, 50 cm below the water, and temperature data were continuously measured and collected during the race.

Speed. The speed was calculated as an average speed on each lap using the official lap time.

Statistical analyses

The normal distribution of the data was checked by the Kolmogorov-Smirnov test. Student's t-test was used to establish the effect of swimmers' characteristics on body composition parameters and T_{core}. Regression analysis with an F-test and the r-squared (r^2) statistic was used to determine the effect of co-variables on T_{core} and variables with p-value ≤ 0.1 in univariate analysis were included in a multiple linear regression for predicting T_{core}. Student's t-test and Fisher's Exact test were used to compare the variables in the H and nH groups and variables with p-value ≤ 0.1 in univariate analysis were included in a multiple logistic regression analysis. The level of significance was fixed at $p<0.05$. To assess the predictive accuracy of early T_{core} change on the risk of dropouts, we tested the area under the curve (AUC) of the receiver operating characteristic (ROC) curve. The correlation between speed and T_{core} was assessed with repeated measures correlations. Statistical analyses were performed with Analyse-it for Microsoft Excel 5.40.2 (Analyse-it Software Ltd, The Tannery, 91 Kirkstall Road, Leeds, LS3 1HS, United Kingdom) and R 3.6.1 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria). Data are presented as the means ±standard deviations (SDs).

RESULTS

Prerace assessments

Participants swam an average of 10 training sessions (i.e., 60 km) per week. Their mean height and weight were 171.9 ±6.6 cm and 65.8 ±8.5 kg, respectively, with a mean BMI of 22.2 ±2.2 kg/m², a mean fat mass of 11.1 ±4.7 kg (i.e., %fat= 16.8 ±6.5%) and a mean muscle mass 26.5 ±5.4 kg (i.e., %muscle= 40.2 ±5.7%).

Performances

Among the 21 participants, 14 swimmers finished the race (nH group, n= 14), 7 dropped out due to hypothermia (H group, n= 7). The mean time for finishers was 6h 03min (best time for men: 5h 26min; best time for women: 5h 37min).

Body core temperature changes

The average T_{core} before the race was 37.5 ±0.3°C. Individual kinetics of T_{core} changes during the race are presented in Figure 1. The average T_{core} drop between the initial T_{core} and lowest T_{core} during the race was -1.4 ±1.3°C with non-statistically different larger values in the H group than in the nH group (-2.1 ±1.5°C vs. -1.1 ±1.0°C, t= -1.53, p= 0.143). The T_{core} at arrival in the nH group was significantly higher than the T_{core} at dropout in the H group (37.0 ±1.0 vs 35.3 ±1.5°C, t= 2.77, p= 0.012), with the lowest T_{core} reached during the race being 32.4°C in a swimmer who was treated by emergency care services. The average T_{core} drop between the initial T_{core} and T_{core} at arrival/dropout was in the -1.9 ±1.5°C in the H group and -0.6 ±1.1°C nH group (t= -2.24, p= 0.037). Regarding perception of cold, the mean CDS scores at arrival were 4.0 ±3.2 in the nH group and 8.1 ±1.5 in the H group (t= -3.15, p= 0.005) with a nonsignificant negative correlation at r= -0.35 (p= 0.125) between CDS and T_{core} drop $_{(end)}$.

Thirty minutes after arrival or dropout, T_{core} was 35.5 ±1.7°C in the H group and 37.0 ±0.6°C in the nH group (t= -2.85, p= 0.010).

Predictive factors of T_{core} drop

The effect of sex on T_{core} before the race (female 37.4 ±0.2°C, male 37.6 ±0.3°C, t= 1.501 p= 0.150) did not reach statistical significance. The drop in T_{core} during the race was larger in male compared to female swimmers (-2.0 ±1.5°C vs. -0.8 ±1.1°C, t= -2.122, p= 0.047). The drop in T_{core} was not correlated with the initial T_{core} (r= -0.03, p= 0.902), age (r= 0.13, p= 0.569), weekly training distance (r= 0.03, p= 0.908), or BMI (r= 0.30, p= 0.194). The drop in T_{core} was however positively correlated with fat mass (r= 0.46, p= 0.034) and %fat mass (r= 0.49, p= 0.024) and negatively correlated with %muscle mass (r= -0.45, p= 0.041) and muscle-to-fat ratio (r= -0.56, p= 0.008). The swimmers who had previously participated in a 25-km race also showed a lower drop than the swimmers who had not previously participated in a 25-km race (-0.45 ±0.94°C vs. -1.78 ±1.40°C, t=2.359, p= 0.029).

After including covariates with p<0.1 in univariate analysis (gender, muscle mass, fat mass and previous participation), the multiple linear regression analysis indicated that the model including fat-mass and previous participation provided the best fit for predicting T_{core} (effect of model: F(2,18)=4.95, p=0.019, T_{core}= -2.99 + 8.01*%fat-mass +0.99*experience[no=0,yes=1], R=0.60), with the respective effects of the covariates %fat-mass (β= 3.77, p= 0.075) and previous participation (β= 3.57, p= 0.075).

Predictive factors for hypothermia-related dropout

The characteristics of the participants among the nH and H groups are presented in the Table 1. The 7 hypothermia-related dropouts included 5 males and 2 females (p= 0.159, Fisher's Exact Test). The rate of hypothermia-related dropouts was 63.6% in swimmers ≤18 years (n= 7 of 11) and null in swimmers above >18 years (n= 0 of 10, p= 0.004, Fisher's Exact Test). The age of swimmers was lower in the H group than in the nH group with a trend toward statistical significance (17.1 ±1.2 vs. 20.4 ±4.12 years, t= -2.00, p= 0.061).

The distance swum per week was lower in the H group than in the nH group, with a trend toward significance (48.9 ±13.3 vs. 66.4 ±15.5 km, t= -2.56 p= 0.019). The rate of hypothermia-related dropouts was 53.8% in swimmers who had never participated (n= 7) and nil in swimmers who had already participated in a 25-km race (n= 0), and Fisher's analysis showed a significant difference in distribution by previous participation in the H and nH groups (p= 0.018).

The difference in BMI of swimmers was not significant in the H group compared with the nH group (21.3 ±1.3 vs. 22.7 ±2.4 kg/m², t= -1.49, p= 0.154). The fat mass parameters were significantly lower in the H group for fat mass (7.2 ±2.4 kg vs. 13.0 ±4.4 kg, t= -3.18, p= 0.005) and %fat mass (11.8 ±4.7% vs. 19.2 ±6.0%, t= -2.88, p= 0.010). The difference in %muscle mass of swimmers was significantly higher in the H group than in the nH group (44.4 ±6.4% vs. 38.2 ±4.3%, t= -2.67, p= 0.016). The body muscle-to-fat ratio of participants was significantly higher in the H group than in the nH group (4.29 ±1.7 vs. 2.33 ±1.3, t= 2.97, p= 0.008).

The initial T_{core} was significantly lower in the H group than in the nH group (37.3 ±0.2°C vs. 37.6 ±0.2°C, t= -2.24, p= 0.037).

To analyze potential confounders, we tested the effect of age (≤18 versus >18 years) and experience (first timers versus experienced swimmers) on the dependent co-variables. Swimmers ≤18 years had lower %fat mass (13.0 ±5.6% vs. 20.9 ±4.9%, t= -3.42, p= 0.003) and had greater %muscle mass (43.1 ±6.3% vs. 37.2 ±3.1%, t= 2.70, p= 0.014). No significant association or difference were found for covariables/cofactors according to experience.

After inclusion of the variables associated with the risk of hypothermia-related dropout with a maximal p-value of 0.10 (age, fat mass, muscle mass, previous participation, initial $T_{core)}$

we ran multiple logistic regression analyses to determine the relative contributions of independent factors to predict the risk of hypothermia-related dropout. The best regression model was found after inclusion of the covariates %fat-mass and initial T_{core} (effect of model: G^2:17.26, df: 2, p<0.001, log odds(H/nH)= 423.18 - 53.86*%fat-mass - 11.11*initial T_{core}, overall prediction 90.5%), with the respective effects of the covariates %fat-mass (p=0.043) and initial T_{core} (p=0.056).

Effect of early changes in T_{core} on the risk of hypothermia-related dropout

To assess the effect of the T_{core} at 2500 m ($T_{core\ (2500)}$) on the risk of hypothermia-related dropout, we ran a ROC analysis. The mean $T_{core\ (2500)}$ was 37.3 ±0.9°C. The ROC curve for $T_{core\ (2500)}$ as a predictor of the risk of hypothermia-related dropout showed that $T_{core\ (2500)}$ had accurate predictive ability to discriminate hypothermia-related dropout (ROC analysis, AUC= 0.806, CI95%: 0.616 - 0.996, p= 0.025). The mean $T_{core\ (2500)}$ was 36.6 ±0.7°C in the H group and 37.6 ±0.8°C in the nH group (t= -2.317, p= 0.032). After interpretation of the Youden index, the $T_{core\ (2500)}$ value with the better predictive parameters was $T_{core\ (2500)} \leq$ 37.1°C (sensitivity: 0.857, specificity: 0.714), and individuals with $T_{core\ (2500)} \leq$ 37.1°C had a 5-fold greater risk of hypothermia-related dropout (Fisher's Exact Test: p= 0.017) (Table 2).

Relations between speed and T_{core} changes during the race

The repeated measures correlation tested the change in T_{core} (e.g. $T_{core\ (5000)}$ - $T_{core\ (2500)}$) in relation to the change in speed (mean $speed_{(lap2)}$- mean $speed_{(lap1)}$) for each lap. The analysis showed a significant positive moderate correlation (r= 0.462, 95% CI: 0.310-0.590, df: 123, p <0.001), so decreasing speed resulted in a significant decrease in T_{core} during the race (Figure 3).

DISCUSSION

The current study showed that a 25-km 25-km OWS competition in 20-20.5°C water (no wetsuits) was associated with a decrease in T_{core} and a high rate of hypothermia-related dropout. Lower initial T_{core} and/or lower body fat as well as premature T_{core} drop ($\leq$ 37.1°C at 2500 m) were associated with an increased risk of hypothermia-related dropout. Moreover, decreasing swimming speed was associated with increased T_{core} drop.

Our results showed that during a 25-km competition at the absolute lowest limit where wetsuits are still banned (20-20.5°C), OW swimmers are exposed to T_{core} drop and hypothermia and confirmed that hypothermia is a common condition in OWS[6,11,19]. Hypothermia was the leading cause of dropout. The nonfinishers' rate has been stable over the years for the French National Open Championship but it is greater than the average dropout rate on the 25km race of the world championships[20] However, it is interesting to note that participants in the Manhattan Island Marathon Swim (46 km, 16-20°C) must be 19 years or older; as all hypothermia-related dropouts were 18 years or younger in our results, this can explain the lower nonfinisher rates of approximately 15% in this event[21].

In our study, a low fat mass and a low initial T_{core} were the most significant independent parameters that were associated with an increased risk of hypothermia-related dropout. From our results, fat mass was the only independent factor associated with T_{core} drop, and swimmers with a lower % fat mass had the greatest T_{core} drop during the race irrespective of gender or BMI. The negative impact of low fat mass on the T_{core} change during cold-water swimming has already been studied[6,19,22], and elite OW swimmers tend to have greater fat mass than triathletes or pool swimmers do[2,23,24]. These physiological and anthropometric differences can explain the older age of peak performance in long-distance swimming compared with shorter distances[25].

As initial T_{core} was predictor of hypothermia-related dropout, it would be interesting to study the effect of pre-race warm-up strategies to increase initial T_{core} on the risk of hypothermia during an OWS race. Also, further studies could explore the impact of the circadian rhythm parameters of body temperature (circadian acrophase, nadir, mesor and amplitude) on OWS performance[26].

Also, the participants who never participated in a 25-km race had greater a T_{core} drop and had greater rates of hypothermia-related dropouts. Higher rates of dropout in novice (vs. experienced) athletes, influenced by psychosocial factors, had previously been described in ultra-trailers, suggesting the importance of preparation and self-efficacy based on past experiences [27]. In OWS, these psychosocial factors should be considered in addition with anthropometric and physiological factors since novice are often the younger participants with low fat mass. These results should draw the attention of professionals on the need to properly prepare novice swimmers for this race and the risk of hypothermia.

Another predictor of hypothermia was a lower initial T_{core} or a premature T_{core} drop under 37.1°C, which was associated with a 5-fold risk of hypothermia-related dropout. Moreover, the decrease in speed during the race was associated with an increased T_{core} drop ($r= 0.46$, $p <0.001$). Among the finishers, 2 swimmers had low T_{core} at 2500m (below 36.0°C), but they could increase their speeds during the lap 2500-5000m and 5000-7500m and their T_{core} remained stable or increased so they were able to finish the race. Also, the 2 swimmers were international level swimmers with previous participation in 25km race and/or longer events, and experience might have enhanced their ability to manage/cope with low T_{core}. Additionally, Tipton el al. (1999) showed that swimming efficiency and length of stroke decreased with T_{core} drop[28]. Thus, pacing strategies in OW-swimmers could be adapted to prevent T_{core} drop and hypothermia outcomes during the race and the vicious cycle of hypothermia and a decrease in speed.

At 30 minutes after dropout in the H group, the T_{core} drop was still at a mean of -1.7°C, even after swimsuits were removed and survival blankets and warming strategies (warm fluids to drink, warm water baths) were used. This suggests a worsening of the T_{core} drop after abandonment, known as 'afterdrop', likely due to the cessation of muscle activity-related heat production[29]. Thus, during the initial stages of rewarming from hypothermia, the vasodilation and increased blood flow associated with exercise-induced hyperemia implies a return of cold blood to the core, causing a further decrease in T_{core} and, also, counteracting the insulating effect of unperfused muscle, which accounts for approximately 70% of total insulation[2]. Additionally, we can hypothesize that the conventional threshold for hypothermia (T_{core} below 35°C) could be less appropriate in certain sport situations, as athletes may drop out for hypothermia with T_{core} above 35°C, and the speed of T_{core} drop or the paradoxical T_{core} drop in response to strenuous exercise can be assimilated to such situations.

These results should be interpreted with caution, as studies in elite athletes have a limited sample size. It was also not possible to control fluid intake in competition, and further interventional studies are needed to evaluate the effect of beverage temperature and hydration strategies[30]. Also, the speed was calculated as the average speed on each lap and the repeated correlation analysis was based on the association between the changes in speed and temperature over each lap. Further research on the association between speed and T_{core} might use GPS devices for stroke count quantification and continuous swimming velocity. Finally, as presented above, our results correspond to a specific situation (20°C, no wetsuit) and may vary in other conditions, and further studies using the same protocol in different environmental situations could be interesting for the assessment of the specific effect of environment.

PRACTICAL APPLICATIONS

Preconditioning warming strategies or avoiding prolonged wait time in cold environments can prevent initial low prerace $T_{core,}$ which is also associated with a higher risk of hypothermia[31]. Further studies are needed to evaluate the effect of individual variations of circadian-rhythm periods and specific preconditioning strategies. Moreover, swimmers could avoid a slow starting speed and significant deceleration during the race to lower the risk of an early T_{core} drop and hypothermia and manage their race avoiding the classical "herd-behavior" of such races[13]. Additionally, medical or organization staff could have specific prevention or management strategies for individuals to identify participants at greater risk and use early predictors (e.g., change in speed) to prevent severe hypothermia. Moreover, medical staff should be aware of hypothermia worsening after cessation of muscle activity and use specific strategies for optimal warming[29]. Finally, our results raise the question of adapting the actual wetsuits guidelines for open water competitions, especially in swimmers at higher risk (e.g., minimal water temperature or type of wetsuit for junior male swimmers).

CONCLUSIONS

In summary, a 25-km OWS race resulted in a significant decrease in $T_{core,}$ with fat mass and experience being associated with T_{core} drop. Additionally, a change in speed, especially a decreased speed, is associated with the T_{core} drop. Fat mass and prerace T_{core} were associated with hypothermia-related dropouts, and participants with early T_{core} drops (≤ 37.1°C at 2500 m) had a 5-fold higher risk of dropping out because of hypothermia. Further studies will focus on optimal strategies for lowering the risk of hypothermia and improving the performance of individuals, especially those with greater risk.

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FIGURE LEGENDS

Figure 1. Changes in core temperature (T_{core}) (a) and speed (b) during the 25-km race among the participants (n= 21)

Figure 2. Repeated measures correlations between change in speed and change in core temperature (T_{core}) during the 25-km race (n= 21)

Table 1. Characteristics of participants in the total group (n= 21) and among groups (nH, n= 14 and H, n= 7)

	Total (n= 21)		nH group (n= 14)		H group (n= 7)		*p-value*
Athletes' characteristics							
Age (years)	19.29	±3.73	20.36	±4.12	17.14	±1.21	*0.061*
Gender							
Female (n & %)	12	57.14%	10	71.43%	2	28.57%	
Male (n & %)	9	42.86%	4	28.57%	5	71.43%	*0.159*
Training							
Distance per week (km, mean ±SD)	60.57	±16.77	66.43	±15.50	48.86	±13.35	*0.019*
Previous completion of a 25 km							
None (n & %)	13	59.09%	6	42.86%	7	100.00%	
1-4 (n & %)	6	31.82%	6	42.86%	0	0.00%	
5-8 (n & %)	2	9.09%	2	14.28%	0	0.00%	*0.018*
Body composition							
Anthropometry							
Height (cm, mean ±SD)	171.88	±6.56	172.00	±5.25	171.64	±9.14	*0.910*
Weight (kg, mean ±SD)	65.79	±9.01	67.34	±9.01	62.71	±6.90	*0.250*
BMI (kg/m², mean ±SD)	22.23	±2.16	22.71	±2.37	21.26	±1.31	*0.154*
Abdominal circumference (cm, mean ±SD)	75.44	±8.78	75.50	±9.93	75.33	±5.69	*0.979*
Fat mass							
Fat mass (kg, mean ±SD)	11.05	±4.71	12.97	±4.43	7.23	±2.41	*0.005*
% fat mass (%, mean ±SD)	16.76	±6.53	19.23	±5.95	11.80	±4.72	*0.010*
Fat-free mass							
Fat-free mass index (kg/m², mean ±SD)	18.52	±1.61	18.42	±1.84	18.74	±1.08	*0.673*
Muscle mass (kg, mean ±SD)	26.54	±5.39	25.81	±5.06	28.01	±6.14	*0.390*
Muscle mass (%, mean ±SD)	40.24	±5.75	38.18	±4.23	44.38	±6.44	*0.016*
Muscle-to-fat ratio (mean ±SD)	2.98	±1.61	2.33	±1.31	4.29	±1.66	*0.008*

BMI: body mass index, SD: standard deviation, nH group: nonhypothermia group, H group: hypothermia group

Table 2. Receiver operating characteristic (ROC) analysis of T_{core} at 2500 m ($T_{core\ (2500)}$) with decision thresholds for predicting hypothermia-related dropout (n= 21)

	$T_{core\ (2500)}$			ROC analysis			Decision thresholds		
	Mean	(SD)	*p*-value	Accuracy (AUC-ROC)	Confidence interval (95%)	*p*-value	**Optimal cut-off**	χ2 statistic	Fisher's test *p*-value
Group							$T_{core\ (2500)} \leq 37.1°C$		
nH group	37.6	(0.8)							
H group	36.6	(0.7)	0.032	0.806	0.616 to 0.996	<0.025		6.857	0.017

AUC: area under the curve, ROC: receiver operating characteristic, SD: standard deviation, nH group: nonhypothermia group, H group: hypothermia group

Risk factors and predictors of hypothermia and dropouts during open water swimming competitions

ABSTRACT

Purpose: To measure the core temperature (T_{core}) in open-water (OW) swimmers during a 25-km competition and identify the predictors of T_{core} drop and hypothermia-related dropouts.

Methods: 24 national and international level OW swimmers participated in the study. Participants completed a personal questionnaire and a body fat / muscle mass assessment before the race. The race consisted in 10 laps over a 2500 m course and speed was calculated as an average speed on each lap. T_{core} was continuously recorded via an ingestible temperature sensor (e-Celsius, BodyCap). Hypothermia-related dropouts (H group) were compared to finishers (nH group).

Results: Average pre-race T_{core} was 37.5 ±0.3°C (n= 21). 7 participants dropped out due to hypothermia (H, n= 7) with a mean T_{core} at dropout of 35.3 ±1.5°C. Multiple logistic regression analysis found that body fat percentage and initial T_{core} were associated with hypothermia- (G^2:17.26, p<0.001). Early T_{core} drop ≤37.1°C at 2500m was associated with a greater rate of hypothermia-related dropouts (71.4% vs. 14.3%, p= 0.017). Multiple linear regression found that body fat percentage and previous participation were associated with T_{core} drop (F= 4.95, p= 0.019). There was a positive correlation between the decrease in speed and T_{core} drop (r= 0.462, p <0.001).

Conclusion: During a OW 25-km competition at 20-21°C, lower initial T_{core} and lower body fat as well as premature T_{core} drop were associated with an increased risk of hypothermia-related

dropout. Lower body fat and no previous participation as well as decrease in swimming speed were associated with T_{core} drop.

INTRODUCTION

Open-water swimming (OWS) characterizes any swimming competition in rivers, lakes, oceans or water channels. The 25-km OWS requires ~5 hours of swimming, during which swimmers must cope with various environmental and physiological parameters (water temperature, race strategies, etc.) that may lead to changes in their body temperature [1,2]. The maintenance of core temperature (T_{core}) while swimming depends on the balance between heat production (related to exercise intensity) and dissipation. However, heat dissipation mechanisms during swimming differ from land sports, as water has a high specific heat and greater conductivity than air, increasing conductive and convective transfer[3]. Thus, unlike other sports in cold air, in which T_{core} increases despite air temperature down to ~0°C[4], swimming in cold water usually results in excessive thermolysis, which may not be compensated by metabolic heat production, leading to a decrease in T_{core}[2].

Hypothermia is broadly defined as an unintentional fall in T_{core} below 35°C and can be classified as mild (T_{core} 32.2-35°C), moderate (32.2-28°C), or severe (<28°C)[5]. Hypothermia has been reported as one of the main causes of dropout or poor performance in OWS[6]. In addition, more than 70% of the deaths in triathlons occur during the swimming phase and are caused by swimming induced pulmonary edema (SIPE) and cardiac arrythmias, most frequently in cold water[2,7]. Of note, fatal events are more frequent during competitions than during leisure or training swims, and it has been hypothesized that an “autonomic conflict” with the coactivation of the sympathetic and parasympathetic drive during cold-water swimming could be worsened by anger-induced sympathetic arousal during competition or mass events[2,8].

To reduce the risk of hypothermia in swimmers, the Fédération Internationale de Natation's (FINA) enacted rules stipulating that water temperature should be at minimum 16°C, and that wetsuits are compulsory when water temperature is <18°C and are allowed when water temperature is <20°C[9]. In addition to environmental factors, hypothermia in athletes may also depend on intrinsic parameters (e.g., sex, age, weight, body composition)[10]. However, few studies have tested elite athletes during competitions[11,12] and the risk factors associated with a decrease in T_{core} and hypothermia-related dropouts during a competitive event remain unknown.

As 25 km is the longest and therefore slowest FINA race at the World Championships [13], it may represent a particular hypothermic challenge to swimmers. Thus, the objectives of the current study were to continuously monitor T_{core} in swimmers during a 25-km race and to identify the potential predictors of T_{core} drop and hypothermia-related dropouts. We hypothesized that OW swimmers are exposed to T_{core} drop during a 25-km competition and that individual parameters (youngest swimmers, male) and/or body composition (low fat mass) could be predictors of T_{core} drop and dropouts.

METHODS

The protocol was validated by the Committee for the Protection of Persons (CPP Sud Méditerranée I Marseille, number 2019-A00542-55 1939) and was registered in an international database (ClinicalTrials.gov NCT04460339). The study was conducted in accordance with the Declaration of Helsinki, and written consent was obtained from all participants, as well as their legal representatives when applicable (i.e., parents for underage participants).

Subjects

Twenty-four (12 males, 12 females; age range 15-32 years old; 6 underage) of the 39 competitors of the 25-km national Open-Water Championship (France, 2019) volunteered for this study. However, one participant did not start due to a muscle-tendinous injury, one participant had incomplete data and one participant dropped out because of muscle pain before mid-race. The characteristics of the 21 remaining participants are presented in Table 1. Ten swimmers were international-level swimmers, and 3 were medalists in international FINA championships. No participants had contraindications to the ingestible temperature sensor including swallowing disorders, transit disorders, or scheduled MRI within 48 hours post event.

Design

Participants completed a personal questionnaire and a body composition assessment the day before the event. They were given an ingestible temperature sensor (e-Celsius®, BodyCap®, Caen, France) with the instructions to swallow it immediately before going to bed, the night before the race. All sensors were checked on the day of the 25-km event, and if the sensor could not be detected, the participant had to swallow another sensor immediately (in five swimmers).

The 25-km race consisted of 10 laps over a 2500 m course with feeding every 1250 m. No instruction was given to the swimmers participating in our study concerning the management of their race. The water temperature was between 20.2°C and 21.0°C during the race, and the use of wetsuits was prohibited. For the nonfinishers, the time of abandonment, mileage swum and cause of abandonment were obtained from the organizing staff (or medical staff if needed), and nonfinishers were also asked about the cause of dropouts and the perception of cold. Hypothermia-related dropouts (H group) were compared to finishers (nH group). Hypothermia-related dropouts were defined as the nonfinishers that were medically diagnosed with hypothermia related symptoms and were provided a medical assessment and treatment. For the other participants, the performance (time) and the final classification on the 25-km race were collected. For all participants, rewarming facilities on the site were heated baths, access to a place of shelter with showers, dry towels and/or blankets, warm beverages and food/fruits

Methodology

Prerace questionnaire. The data collected were sex, age, level of competition, best performance, average number of training sessions per week and total swimming distance per week.

Body composition. Fat mass (in kg, index and % of body mass), fat-free mass (in kg, index and % of body mass) and muscle mass (total, trunk and upper-lower limbs) were estimated using bioelectrical impedance analysis (mBCA 525, Seca, Germany). Body muscle-to-fat ratio was calculated as total muscle mass: fat mass. Measurements were performed in the supine position using eight electrodes on both sides with the subject lying on a nonconductive surface[14]. Adhesive gel electrodes (Kendall, H59P, Covidien IIc, Mansfield, MA, USA) were placed at defined anatomical sites on the dorsal surfaces of the hand, wrist, ankle and foot according to the manufacturer's instructions.

Core temperature. Gastrointestinal temperature was monitored using an ingestible electronic sensor (e-Celsius, BodyCap, Caen, France) that provides a continuous, reliable and validated measurement of T_{core} [15]. This system has previously been used to monitor elite athletes in official competitions performed in hot[16] and cold environments[4], and has also been used to monitor T_{core} in young adolescents[17]. Temperature was monitored every 30 s with the data being stored within the ingestible sensor and downloaded to an external receiver after the race (e-Viewer®, BodyCap, Caen, France).

Perceptual responses. Immediately at the end of the race, participants' perception of cold was assessed using the Cold Discomfort Scale (CDS), which is a reliable and valid subjective judgment scale for the assessment of patient thermal state in a cold environment and ranges from 0 (no perception of cold) to 10 (maximum feeling of cold)[18].

Water temperature. I-buttons (iButton® Maxim Integrated) were attached to the buoys delineating the course of the event, 50 cm below the water, and temperature data were continuously measured and collected during the race.

Speed. The speed was calculated as an average speed on each lap using the official lap time.

Statistical analyses

The normal distribution of the data was checked by the Kolmogorov-Smirnov test. Student's t-test was used to establish the effect of swimmers' characteristics on body composition parameters and T_{core}. Regression analysis with an F-test and the r-squared (r^2) statistic was used to determine the effect of co-variables on T_{core} and variables with p-value ≤ 0.1 in univariate analysis were included in a multiple linear regression for predicting T_{core}. Student's t-test and Fisher's Exact test were used to compare the variables in the H and nH groups and variables with p-value ≤ 0.1 in univariate analysis were included in a multiple logistic regression analysis. The level of significance was fixed at $p<0.05$. To assess the predictive accuracy of early T_{core} change on the risk of dropouts, we tested the area under the curve (AUC) of the receiver operating characteristic (ROC) curve. The correlation between speed and T_{core} was assessed with repeated measures correlations. Statistical analyses were performed with Analyse-it for Microsoft Excel 5.40.2 (Analyse-it Software Ltd, The Tannery, 91 Kirkstall Road, Leeds, LS3 1HS, United Kingdom) and R 3.6.1 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria). Data are presented as the means ±standard deviations (SDs).

RESULTS

Prerace assessments

Participants swam an average of 10 training sessions (i.e., 60 km) per week. Their mean height and weight were 171.9 ±6.6 cm and 65.8 ±8.5 kg, respectively, with a mean BMI of 22.2 ±2.2 kg/m², a mean fat mass of 11.1 ±4.7 kg (i.e., %fat= 16.8 ±6.5%) and a mean muscle mass 26.5 ±5.4 kg (i.e., %muscle= 40.2 ±5.7%).

Performances

Among the 21 participants, 14 swimmers finished the race (nH group, n= 14), 7 dropped out due to hypothermia (H group, n= 7). The mean time for finishers was 6h 03min (best time for men: 5h 26min; best time for women: 5h 37min).

Body core temperature changes

The average T_{core} before the race was 37.5 ±0.3°C. Individual kinetics of T_{core} changes during the race are presented in Figure 1. The average T_{core} drop between the initial T_{core} and lowest T_{core} during the race was -1.4 ±1.3°C with non-statistically different larger values in the H group than in the nH group (-2.1 ±1.5°C vs. -1.1 ±1.0°C, t= -1.53, p= 0.143). The T_{core} at arrival in the nH group was significantly higher than the T_{core} at dropout in the H group (37.0 ±1.0 vs 35.3 ±1.5°C, t= 2.77, p= 0.012), with the lowest T_{core} reached during the race being 32.4°C in a swimmer who was treated by emergency care services. The average T_{core} drop between the initial T_{core} and T_{core} at arrival/dropout was in the -1.9 ±1.5°C in the H group and -0.6 ±1.1°C nH group (t= -2.24, p= 0.037). Regarding perception of cold, the mean CDS scores at arrival were 4.0 ±3.2 in the nH group and 8.1 ±1.5 in the H group (t= -3.15, p= 0.005) with a nonsignificant negative correlation at r= -0.35 (p= 0.125) between CDS and T_{core} drop $_{(end)}$.

Thirty minutes after arrival or dropout, T_{core} was 35.5 ±1.7°C in the H group and 37.0 ±0.6°C in the nH group (t= -2.85, p= 0.010).

Predictive factors of T_{core} drop

The effect of sex on T_{core} before the race (female 37.4 ±0.2°C, male 37.6 ±0.3°C, t= 1.501 p= 0.150) did not reach statistical significance. The drop in T_{core} during the race was larger in male compared to female swimmers (-2.0 ±1.5°C vs. -0.8 ±1.1°C, t= -2.122, p= 0.047). The drop in T_{core} was not correlated with the initial T_{core} (r= -0.03, p= 0.902), age (r= 0.13, p= 0.569), weekly training distance (r= 0.03, p= 0.908), or BMI (r= 0.30, p= 0.194). The drop in T_{core} was however positively correlated with fat mass (r= 0.46, p= 0.034) and %fat mass (r= 0.49, p= 0.024) and negatively correlated with %muscle mass (r= -0.45, p= 0.041) and muscle-to-fat ratio (r= -0.56, p= 0.008). The swimmers who had previously participated in a 25-km race also showed a lower drop than the swimmers who had not previously participated in a 25-km race (-0.45 ±0.94°C vs. -1.78 ±1.40°C, t=2.359, p= 0.029).

After including covariates with p<0.1 in univariate analysis (gender, muscle mass, fat mass and previous participation), the multiple linear regression analysis indicated that the model including fat-mass and previous participation provided the best fit for predicting T_{core} (effect of model: F(2,18)= 4.95, p=0.019, T_{core}= -2.99 + 8.01*%fat-mass +0.99*experience[no=0,yes=1], R=0.60), with the respective effects of the covariates %fat-mass (β= 3.77, p= 0.075) and previous participation (β= 3.57, p= 0.075).

Predictive factors for hypothermia-related dropout

The characteristics of the participants among the nH and H groups are presented in the Table 1. The 7 hypothermia-related dropouts included 5 males and 2 females (p= 0.159, Fisher's Exact Test). The rate of hypothermia-related dropouts was 63.6% in swimmers ≤18 years (n= 7 of 11) and null in swimmers above >18 years (n= 0 of 10, p= 0.004, Fisher's Exact Test). The age of swimmers was lower in the H group than in the nH group with a trend toward statistical significance (17.1 ±1.2 vs. 20.4 ±4.12 years, t= -2.00, p= 0.061).

The distance swum per week was lower in the H group than in the nH group, with a trend toward significance (48.9 ±13.3 vs. 66.4 ±15.5 km, t= -2.56 p= 0.019). The rate of hypothermia-related dropouts was 53.8% in swimmers who had never participated (n= 7) and nil in swimmers who had already participated in a 25-km race (n= 0), and Fisher's analysis showed a significant difference in distribution by previous participation in the H and nH groups (p= 0.018).

The difference in BMI of swimmers was not significant in the H group compared with the nH group (21.3 ±1.3 vs. 22.7 ±2.4 kg/m², t= -1.49, p= 0.154). The fat mass parameters were significantly lower in the H group for fat mass (7.2 ±2.4 kg vs. 13.0 ±4.4 kg, t= -3.18, p= 0.005) and %fat mass (11.8 ±4.7% vs. 19.2 ±6.0%, t= -2.88, p= 0.010). The difference in %muscle mass of swimmers was significantly higher in the H group than in the nH group (44.4 ±6.4% vs. 38.2 ±4.3%, t= -2.67, p= 0.016). The body muscle-to-fat ratio of participants was significantly higher in the H group than in the nH group (4.29 ±1.7 vs. 2.33 ±1.3, t= 2.97, p= 0.008).

The initial T_{core} was significantly lower in the H group than in the nH group (37.3 ±0.2°C vs. 37.6 ±0.2°C, t= -2.24, p= 0.037).

To analyze potential confounders, we tested the effect of age (≤18 versus >18 years) and experience (first timers versus experienced swimmers) on the dependent co-variables. Swimmers ≤18 years had lower %fat mass (13.0 ±5.6% vs. 20.9 ±4.9%, t= -3.42, p= 0.003) and had greater %muscle mass (43.1 ±6.3% vs. 37.2 ±3.1%, t= 2.70, p= 0.014). No significant association or difference were found for covariables/cofactors according to experience.

After inclusion of the variables associated with the risk of hypothermia-related dropout with a maximal p-value of 0.10 (age, fat mass, muscle mass, previous participation, initial T_{core})

we ran multiple logistic regression analyses to determine the relative contributions of independent factors to predict the risk of hypothermia-related dropout. The best regression model was found after inclusion of the covariates %fat-mass and initial T_{core} (effect of model: G^2:17.26, df: 2, p<0.001, log odds(H/nH)= 423.18 - 53.86*%fat-mass - 11.11*initial $T_{core,}$ overall prediction 90.5%), with the respective effects of the covariates %fat-mass (p=0.043) and initial T_{core} (p=0.056).

Effect of early changes in T_{core} on the risk of hypothermia-related dropout

To assess the effect of the T_{core} at 2500 m ($T_{core\ (2500)}$) on the risk of hypothermia-related dropout, we ran a ROC analysis. The mean $T_{core\ (2500)}$ was 37.3 ±0.9°C. The ROC curve for $T_{core\ (2500)}$ as a predictor of the risk of hypothermia-related dropout showed that $T_{core\ (2500)}$ had accurate predictive ability to discriminate hypothermia-related dropout (ROC analysis, AUC= 0.806, CI95%: 0.616 - 0.996, p= 0.025). The mean $T_{core\ (2500)}$ was 36.6 ±0.7°C in the H group and 37.6 ±0.8°C in the nH group (t= -2.317, p= 0.032). After interpretation of the Youden index, the $T_{core\ (2500)}$ value with the better predictive parameters was $T_{core\ (2500)} \leq$ 37.1°C (sensitivity: 0.857, specificity: 0.714), and individuals with $T_{core\ (2500)} \leq$ 37.1°C had a significantly greater rate of hypothermia-related dropouts (85.7%, Fisher's Exact Test: p= 0.017) (Table 2).

Relations between speed and T_{core} changes during the race

The repeated measures correlation tested the change in T_{core} (e.g. $T_{core\ (5000)}$ - $T_{core\ (2500)}$) in relation to the change in speed (mean $speed_{(lap2)}$- mean $speed_{(lap1)}$) for each lap. The analysis showed a significant positive moderate correlation (r= 0.462, 95% CI: 0.310-0.590, df: 123, p <0.001), so decreasing speed resulted in a significant decrease in T_{core} during the race (Figure 3).

DISCUSSION

The current study showed that a 25-km 25-km OWS competition in 20-20.5°C water (no wetsuits) was associated with a decrease in T_{core} and a high rate of hypothermia-related dropout. Lower initial T_{core} and/or lower body fat as well as premature T_{core} drop (≤ 37.1°C at 2500 m) were associated with an increased risk of hypothermia-related dropout. Moreover, decreasing swimming speed was associated with increased T_{core} drop.

Our results showed that during a 25-km competition at the absolute lowest limit where wetsuits are still banned (20-20.5°C), OW swimmers are exposed to T_{core} drop and hypothermia and confirmed that hypothermia is a common condition in OWS[6,11,19]. Hypothermia was the leading cause of dropout. The nonfinishers' rate has been stable over the years for the French National Open Championship but it is greater than the average dropout rate on the 25km race of the world championships[20] However, it is interesting to note that participants in the Manhattan Island Marathon Swim (46 km, 16-20°C) must be 19 years or older; as all hypothermia-related dropouts were 18 years or younger in our results, this can explain the lower nonfinisher rates of approximately 15% in this event[21].

In our study, a low fat mass and a low initial T_{core} were the most significant independent parameters that were associated with an increased risk of hypothermia-related dropout. From our results, fat mass was the only independent factor associated with T_{core} drop, and swimmers with a lower % fat mass had the greatest T_{core} drop during the race irrespective of gender or BMI. The negative impact of low fat mass on the T_{core} change during cold-water swimming has already been studied[6,19,22], and elite OW swimmers tend to have greater fat mass than triathletes or pool swimmers do[2,23,24]. These physiological and anthropometric differences can explain the older age of peak performance in long-distance swimming compared with shorter distances[25].

As initial T_{core} was predictor of hypothermia-related dropout, it would be interesting to study the effect of pre-race warm-up strategies to increase initial T_{core} on the risk of hypothermia during an OWS race. Also, further studies could explore the impact of the circadian rhythm parameters of body temperature (circadian acrophase, nadir, mesor and amplitude) on OWS performance[26].

Also, the participants who never participated in a 25-km race had greater a T_{core} drop and had greater rates of hypothermia-related dropouts. Higher rates of dropout in novice (vs. experienced) athletes, influenced by psychosocial factors, had previously been described in ultra-trailers, suggesting the importance of preparation and self-efficacy based on past experiences [27]. In OWS, these psychosocial factors should be considered in addition with anthropometric and physiological factors since novice are often the younger participants with low fat mass. These results should draw the attention of professionals on the need to properly prepare novice swimmers for this race and the risk of hypothermia.

Another predictor of hypothermia was a lower initial T_{core} or a premature T_{core} drop under 37.1°C, which was associated with a 5-fold risk of hypothermia-related dropout. Moreover, the decrease in speed during the race was associated with an increased T_{core} drop ($r= 0.46$, $p <0.001$). Among the finishers, 2 swimmers had low T_{core} at 2500m (below 36.0°C), but they could increase their speeds during the lap 2500-5000m and 5000-7500m and their T_{core} remained stable or increased so they were able to finish the race. Also, the 2 swimmers were international level swimmers with previous participation in 25km race and/or longer events, and experience might have enhanced their ability to manage/cope with low T_{core}. Additionally, Tipton el al. (1999) showed that swimming efficiency and length of stroke decreased with T_{core} drop[28]. Thus, pacing strategies in OW-swimmers could be adapted to prevent T_{core} drop and hypothermia outcomes during the race and the vicious cycle of hypothermia and a decrease in speed.

At 30 minutes after dropout in the H group, the T_{core} drop was still at a mean of -1.7°C, even after swimsuits were removed and survival blankets and warming strategies (warm fluids to drink, warm water baths) were used. This suggests a worsening of the T_{core} drop after abandonment, known as 'afterdrop', likely due to the cessation of muscle activity-related heat production[29]. Thus, during the initial stages of rewarming from hypothermia, the vasodilation and increased blood flow associated with exercise-induced hyperemia implies a return of cold blood to the core, causing a further decrease in T_{core} and, also, counteracting the insulating effect of unperfused muscle, which accounts for approximately 70% of total insulation[2]. Additionally, we can hypothesize that the conventional threshold for hypothermia (T_{core} below 35°C) could be less appropriate in certain sport situations, as athletes may drop out for hypothermia with T_{core} above 35°C, and the speed of T_{core} drop or the paradoxical T_{core} drop in response to strenuous exercise can be assimilated to such situations.

These results should be interpreted with caution, as studies in elite athletes have a limited sample size. It was also not possible to control fluid intake in competition, and further interventional studies are needed to evaluate the effect of beverage temperature and hydration strategies[30]. Also, the speed was calculated as the average speed on each lap and the repeated correlation analysis was based on the association between the changes in speed and temperature over each lap. Further research on the association between speed and T_{core} might use GPS devices for stroke count quantification and continuous swimming velocity. Finally, as presented above, our results correspond to a specific situation (20°C, no wetsuit) and may vary in other conditions, and further studies using the same protocol in different environmental situations could be interesting for the assessment of the specific effect of environment.

PRACTICAL APPLICATIONS

Preconditioning warming strategies or avoiding prolonged wait time in cold environments can prevent initial low prerace $T_{core,}$ which is also associated with a higher risk of hypothermia[31]. Further studies are needed to evaluate the effect of individual variations of circadian-rhythm periods and specific preconditioning strategies. Moreover, swimmers could avoid a slow starting speed and significant deceleration during the race to lower the risk of an early T_{core} drop and hypothermia and manage their race avoiding the classical "herd-behavior" of such races[13]. Additionally, medical or organization staff could have specific prevention or management strategies for individuals to identify participants at greater risk and use early predictors (e.g., change in speed) to prevent severe hypothermia. Moreover, medical staff should be aware of hypothermia worsening after cessation of muscle activity and use specific strategies for optimal warming[29]. Finally, our results raise the question of adapting the actual wetsuits guidelines for open water competitions, especially in swimmers at higher risk (e.g., minimal water temperature or type of wetsuit for junior male swimmers).

CONCLUSIONS

In summary, a 25-km OWS race resulted in a significant decrease in $T_{core,}$ with fat mass and experience being associated with T_{core} drop. Additionally, a change in speed, especially a decreased speed, is associated with the T_{core} drop. Fat mass and prerace T_{core} were associated with hypothermia-related dropouts, and participants with early T_{core} drops (≤ 37.1°C at 2500 m) had a 5-fold higher risk of dropping out because of hypothermia. Further studies will focus on optimal strategies for lowering the risk of hypothermia and improving the performance of individuals, especially those with greater risk.

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FIGURE LEGENDS

Figure 1. Changes in core temperature (T_{core}) (a) and speed (b) during the 25-km race among the participants (n= 21)

Figure 2. Repeated measures correlations between change in speed and change in core temperature (T_{core}) during the 25-km race (n= 21)

Table 1. Characteristics of participants in the total group (n= 21) and among groups (nH, n= 14 and H, n= 7)

	Total (n= 21)		nH group (n= 14)		H group (n= 7)		*p-value*
Athletes' characteristics							
Age (years)	19.29	±3.73	20.36	±4.12	17.14	±1.21	*0.061*
Gender							
Female (n & %)	12	57.14%	10	71.43%	2	28.57%	
Male (n & %)	9	42.86%	4	28.57%	5	71.43%	*0.159*
Training							
Distance per week (km, mean ±SD)	60.57	±16.77	66.43	±15.50	48.86	±13.35	*0.019*
Previous completion of a 25 km							
None (n & %)	13	59.09%	6	42.86%	7	100.00%	
1-4 (n & %)	6	31.82%	6	42.86%	0	0.00%	
5-8 (n & %)	2	9.09%	2	14.28%	0	0.00%	*0.018*
Body composition							
Anthropometry							
Height (cm, mean ±SD)	171.88	±6.56	172.00	±5.25	171.64	±9.14	*0.910*
Weight (kg, mean ±SD)	65.79	±9.01	67.34	±9.01	62.71	±6.90	*0.250*
BMI (kg/m², mean ±SD)	22.23	±2.16	22.71	±2.37	21.26	±1.31	*0.154*
Abdominal circumference (cm, mean ±SD)	75.44	±8.78	75.50	±9.93	75.33	±5.69	*0.979*
Fat mass							
Fat mass (kg, mean ±SD)	11.05	±4.71	12.97	±4.43	7.23	±2.41	*0.005*
% fat mass (%, mean ±SD)	16.76	±6.53	19.23	±5.95	11.80	±4.72	*0.010*
Fat-free mass							
Fat-free mass index (kg/m², mean ±SD)	18.52	±1.61	18.42	±1.84	18.74	±1.08	*0.673*
Muscle mass (kg, mean ±SD)	26.54	±5.39	25.81	±5.06	28.01	±6.14	*0.390*
Muscle mass (%, mean ±SD)	40.24	±5.75	38.18	±4.23	44.38	±6.44	*0.016*
Muscle-to-fat ratio (mean ±SD)	2.98	±1.61	2.33	±1.31	4.29	±1.66	*0.008*

BMI: body mass index, SD: standard deviation, nH group: nonhypothermia group, H group: hypothermia group

Table 2. Receiver operating characteristic (ROC) analysis of T_{core} at 2500 m ($T_{core\ (2500)}$) with decision thresholds for predicting hypothermia-related dropout (n= 21)

	$T_{core\ (2500)}$			ROC analysis			Decision thresholds		
	Mean	(SD)	*p*-value	Accuracy (AUC-ROC)	Confidence interval (95%)	*p*-value	**Optimal cut-off**	χ2 statistic	Fisher's test *p*-value
Group							$T_{core\ (2500)} \leq 37.1°C$		
nH group									
	37.6	(0.8)							
H group	36.6	(0.7)	0.032	0.806	0.616 to 0.996	<0.025		6.857	0.017

AUC: area under the curve, ROC: receiver operating characteristic, SD: standard deviation, nH group: nonhypothermia group, H group: hypothermia group

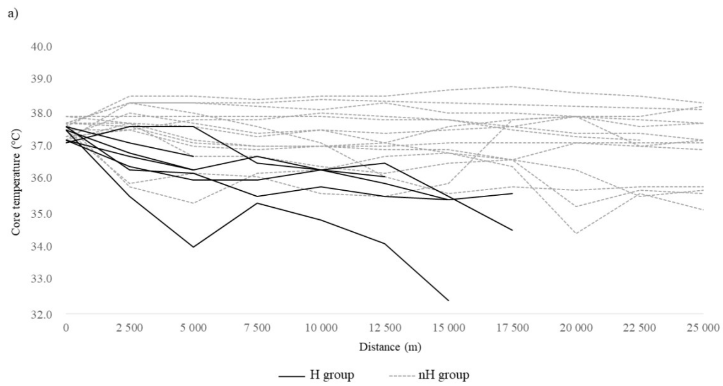
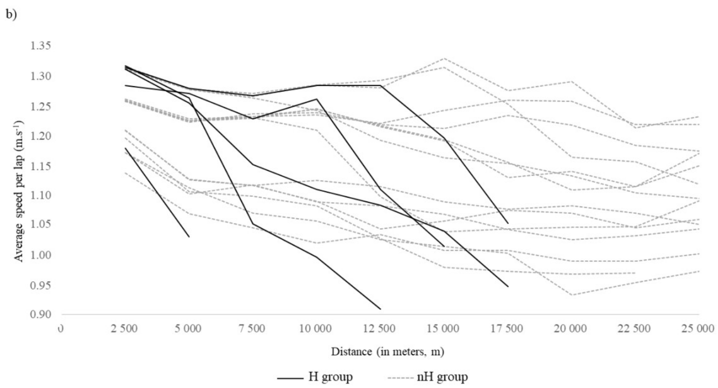


Figure 1 . Changes in core temperature (Tcore) (a) and speed (b) during the 25-km race among the participants (n= 21)

338x190mm (96 x 96 DPI)



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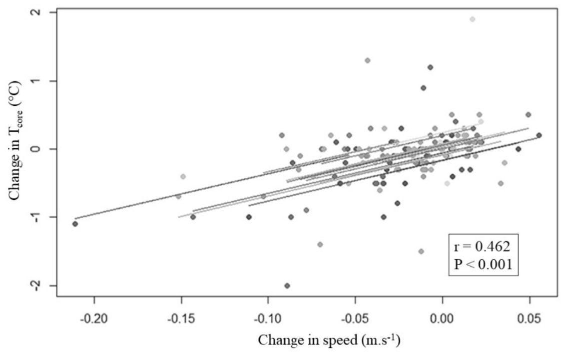

Figure 2. Repeated measures correlations between change in speed and change in core temperature (Tcore) during the 25-km race (n= 21)

338x190mm (96 x 96 DPI)

Table 1. Characteristics of participants in the total group (n= 21) and among groups (nH, n= 14 and H, n= 7)

	Total (n= 21)		nH group (n= 14)		H group (n= 7)		*p-value*
Athletes' characteristics							
Age (years)	19.29	±3.73	20.36	±4.12	17.14	±1.21	*0.061*
Gender							
Female (n & %)	12	57.14%	10	71.43%	2	28.57%	
Male (n & %)	9	42.86%	4	28.57%	5	71.43%	*0.159*
Training							
Distance per week (km, mean ±SD)	60.57	±16.77	66.43	±15.50	48.86	±13.35	*0.019*
Previous completion of a 25 km							
None (n & %)	13	59.09%	6	42.86%	7	100.00%	
1-4 (n & %)	6	31.82%	6	42.86%	0	0.00%	
5-8 (n & %)	2	9.09%	2	14.28%	0	0.00%	*0.018*
Body composition							
Anthropometry							
Height (cm, mean ±SD)	171.88	±6.56	172.00	±5.25	171.64	±9.14	*0.910*
Weight (kg, mean ±SD)	65.79	±9.01	67.34	±9.01	62.71	±6.90	*0.250*
BMI (kg/m², mean ±SD)	22.23	±2.16	22.71	±2.37	21.26	±1.31	*0.154*
Abdominal circumference (cm, mean ±SD)	75.44	±8.78	75.50	±9.93	75.33	±5.69	*0.979*
Fat mass							
Fat mass (kg, mean ±SD)	11.05	±4.71	12.97	±4.43	7.23	±2.41	*0.005*
% fat mass (%, mean ±SD)	16.76	±6.53	19.23	±5.95	11.80	±4.72	*0.010*
Fat-free mass							
Fat-free mass index (kg/m², mean ±SD)	18.52	±1.61	18.42	±1.84	18.74	±1.08	*0.673*
Muscle mass (kg, mean ±SD)	26.54	±5.39	25.81	±5.06	28.01	±6.14	*0.390*
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	Mean	(SD)	*p*-value	Accuracy (AUC-ROC)	Confidence interval (95%)	*p*-value	**Optimal cut-off**	$\chi 2$ statistic	Fisher's test *p*-value
Group							$T_{core\ (2500)} \leq 37.1°C$		
nH group									
	37.6	(0.8)							
H group	36.6	(0.7)	0.032	0.806	0.616 to 0.996	<0.025		6.857	0.017

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