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Endurance Capacity Impairment in Cold Air Ranging from Skin Cooling to Mild Hypothermia

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Running Head: Cold Strain and Endurance Capacity

Abstract

Introduction: We tested the effects of cold air (0°C) exposure on endurance capacity to different levels of cold strain ranging from skin cooling to core cooling of Δ-1.0°C. **Methods:** Ten males completed a randomized, crossover, control study consisting of a cycling time-to-exhaustion (TTE) at 70% of their peak power output following: i) 30-min of exposure to 22°C thermoneutral air (TN), ii) 30-min exposure to 0°C air leading to a cold shell (CS), iii) 0°C air exposure causing mild hypothermia of -0.5°C from baseline rectal temperature (HYPO-0.5°C), and iv) 0°C air exposure causing mild hypothermia of -1.0°C from baseline rectal temperature (HYPO-1.0°C). The latter three conditions tested TTE in 0°C air. **Results:** Core temperature and seven-site mean skin temperature at the start of the TTE were: TN (37.0 ± 0.2°C, 31.2 ± 0.8°C), CS (37.1 ± 0.3°C, 25.5 ± 1.4°C), HYPO-0.5°C (36.6 ± 0.4°C, 22.3 ± 2.2°C), HYPO-1.0°C (36.4 ± 0.5°C, 21.4 ± 2.7°C). There was a significant condition effect ($p \leq 0.001$) for TTE, which from TN (23.75 ± 13.75 min) to CS (16.22 ± 10.30 min, Δ-30.9 ± 21.5%, p=0.055), HYPO-0.5°C (8.50 ± 5.23 min, Δ-61.4 ± 19.7%, $p \leq 0.001$), and HYPO-1.0°C (6.50 ± 5.60 min, Δ-71.6 ± 16.4%, $p \leq 0.001$). Furthermore, participants had a greater endurance capacity in CS compared to HYPO-0.5°C (p=0.046), and HYPO-1.0°C (p=0.007), with no differences between HYPO-0.5°C and HYPO-1.0°C (p=1.00). **Conclusion:** Endurance capacity impairment at 70% peak power output occurs early in cold exposure with skin cooling, with significantly larger impairments with mild hypothermia up to Δ-1.0°C.

NEW & NOTEWORTHY: We developed a novel protocol that cooled skin temperature, or skin plus core temperature (Δ-0.5°C or Δ-1.0°C), to determine a dose-response of cold exposure on endurance capacity at 70% peak power output. Skin cooling significantly impaired exercise tolerance time by ~31%, whereas core cooling led to a further reduction of 30-40% with no

difference between Δ-0.5°C or Δ-1.0°C. Overall, simply cooling the skin impaired endurance capacity, but this impairment is further magnified by core cooling.

Keywords: Core Cooling; Mild Hypothermia; Endurance Capacity; Cold Strain; Heat Debt

Introduction

Athletes, military personal, and occupational workers can train, compete, and work in cold environments where it is important to understand how physical capacity is altered in the cold in order to maintain performance, prevent accidents and injuries, and prevent thermal strain. Exercise in cold air combined with inadequate clothing is physiologically more demanding compared to thermoneutral environments due to changes in cardiorespiratory function (e.g., vasoconstriction, shifts in oxygen dissociation, reduced peak oxygen consumption) (1, 2), increased metabolic demands (if shivering is present) (3, 4), and reduced neuromuscular function, coordination, and contractility (5–7). Despite these physiological changes with cold exposure, data concerning performance changes are equivocal, with time-to-exhaustion (TTE) at ~70% of maximal aerobic capacity either being similar between 4°C and 21°C air (8) or improved by ~40% in 3°C (9) compared to 20°C. One potential cause of these disparate findings may be a lack of significant skin or core temperature cooling prior to exercise, as these were acute exposure protocols where exercise commenced almost immediately upon entry to a cold environment, likely resulting in little to no change in core or muscle temperature. Recently, studies inducing actual mild hypothermia pre-exercise demonstrate a performance decrement, with ~Δ-1.5°C in core temperature via cold-water immersion (10°C) reducing the work completed by ~11% during a 20-min self-paced cycling time trial in a thermoneutral environment (23°C) (10). Similarly, an ~Δ-0.5°C in core temperature via cold-air exposure impaired 15-km time trial performance in trained cyclists in cold air (0°C) (1). Given that ratings of perceived exertion remained similar in the latter study, the ~6% lower average power output suggests a voluntary down-regulation of workload in the face of elevated thermal discomfort, indicating that individuals may not be able to sustain the same absolute workload as thermoneutral environments.

In acute cold exposures combined with inadequate clothing, individuals first experience cooling of the overall skin/ outer shell temperature, followed cooling of core temperature if there is insufficient heat production to offset heat loss. It is currently unknown if there is a cold exposure dose response exists between peripheral versus deep core cooling, or the magnitude of core cooling on endurance capacity in the cold. Endurance performance is physiologically determined by mechanical efficiency, anaerobic capacity, and the oxygen transport cascade (11), with the latter known to be regulated in the cold via lower perfusion (capillary vasoconstriction), peripheral resistance, and diffusion (lower intracellular reaction rates and greater kinematic viscosity) capacity (12, 13). Cooling skin or outer shell temperature alone increases peripheral vasoconstriction, and decreases muscle blood flow and oxygenation (14, 15), and increases lactate accumulation while decreasing lactate threshold during exercise (16). Exercise impairment may be caused directly from a cold shell, as using a heated jacket to maintain whole-body skin temperature has been shown to improve 2-km rowing time-trial performance following 25-min of passive cold air exposure (8°C) (17). Greater cold strain from further core cooling to mild hypothermia elicits shivering and further increase heart rate, thermal discomfort, and vasoconstriction and decreased oxygen availability (1–3, 18), potentially leading to greater impairments in endurance capacity. Peak aerobic capacity during combined arm/leg ergometry is demonstrated to decline ~5-6% per °C decrease in core temperature (19). However, the separate and combined effects of cooling skin/shell and core temperature on endurance capacity in cold air is unknown.

One of the inherent methodological challenges in cold physiology research is normalizing the cold strain between individuals. A set duration protocol (e.g. 120-mins) can lead to wide individual variability in actual core cooling, due to such factors as anthropometrics (body mass, surface-area to mass ratio, fat insulation), age, and sex, which influences cooling rates (For review see (20)). An alternative approach is to cool individuals to a set decrease in baseline core temperature (e.g. Δ-0.5°C) (1, 2, 18) to normalize cold strain. However, this approach can lead to interindividual variability in cooling times, as recently we demonstrated that cooling core temperature to Δ-0.8°C from baseline in cold air (0°C) ranged from 89-173 minutes across participants (Wallace et al., Unpublished Data). The differences in cold exposure/cooling times prior to exercise may introduce additional confounding variables related to cooling that may influence performance. For example, cooling leads to an increase in shivering, which increases metabolic heat production to offset heat loss, thus leading to more energy expended prior to and during exercise. Critically, changes in core temperature are determined by the cumulative imbalance between metabolic heat production and net heat loss (i.e., body heat storage), body mass (i.e., internal heat sink) and body composition (i.e., specific heat capacity of body tissues) (21). In cold environments, partitional calorimetry is used to calculate the rate of heat storage ($\dot{S}$, where positive values indicates heat gain, negative values indicate heat loss), and can be used to estimate heat debt (HD), which represents the cumulative change in whole- body heat content and provides an indication of cold strain (22–24). The use of HD as a physiological measure has primarily been used to measure the thermoregulatory response to cold air following repeated cold water immersion (24, 25) or high intensity interval training (26). This tool can be used to provide an index of cold strain between participants and between different levels of core cooling and can encapsulate confounds of different cooling times based on body surface area, heat production, and avenues of heat loss over a cold exposure. Therefore, the inclusion of HD prior to exercise may provide insight regarding the level of cold strain and ultimately its effect on performance beyond thermometric changes in core and skin temperature alone by determining both metabolic heat production and loss.

The purpose of this study was to test the effects of cold air (0°C) exposure, ranging from initial cooling of the shell to two levels of mild hypothermia, on endurance capacity. We tested time to exhaustion (TTE) at 70% of peak power output in four randomized conditions: i) a 30-min exposure to 22°C thermoneutral air (TN), ii) an acute ~30-min exposure to 0°C air leading to a cold shell (CS) and neutral core, iii) a 0°C air exposure causing mild hypothermia of Δ-0.5°C from baseline rectal temperature (T_{re}) (HYPO-0.5°C), and iv) a 0°C air exposure causing mild hypothermia of Δ-1.0°C from baseline T_{re} (HYPO-1.0°C). We hypothesized that: i) endurance capacity would be impaired with CS compared with thermoneutral; ii) both core cooling conditions will decrease endurance capacity more than skin cooling alone; and iii) HYPO-1.0°C will lead to greater impairments in endurance capacity compared to HYPO-0.5°C due to increased cold strain.

Methods

Participants - The experimental protocol was cleared by the Research Ethics Board at Brock University (REB# 19-026) and conformed to the latest revision of the Declaration of Helsinki. Ten healthy male volunteers (See Table 1 for characteristics), who were free from cardiovascular, respiratory, neurological, and cold disorders were recruited from the university and community population. All participants were informed of the experimental protocol and associated risks before participating in this experiment and provided both verbal and written informed consent. Participants were allowed to withdraw their participation at any point and their data up until data collection was completed as data was de-identified.

Experimental Design – The experiment was a randomized, crossover, control trial consisting of two familiarization sessions and 4 experimental sessions. The first familiarization session involved collecting anthropometric measures, determining peak oxygen consumption, peak power output, and practicing the TTE. The second familiarization provided two further practices of the TTE. The 4 experimental conditions were separated by 3-7 days to minimize the potential of cold acclimation and performed at the same time of day to control for circadian fluctuations in core temperature. Participants were instructed to avoid vigorous exercise and alcohol consumption 24 hours and caffeine 6 hours prior to each session.

[Insert Table 1 About Here]

Familiarization Trials – Upon arrival for the 1st familiarization trial, anthropometric measurements of height (cm), mass (kg), body surface area (m^2), and % body fat from 7-site skinfold were obtained. An incremental test to exhaustion was performed on a cycle ergometer (Velotron, RacerMate Inc, USA) to determine peak oxygen consumption and peak power output (PPO). The test began with a standardized 5-min warm-up at 100 W, followed by workload increase of 25 W each minute until exhaustion. Peak oxygen consumption ($\dot{V}O_{2\,peak}$) was defined as the highest continuous 30-s value measured breath-by-breath from expired gases collected through a soft silicone facemask connected to an inline gas collection system (see details below). The final stage completed was considered PPO (W). Following warm down and ~30-min passive recovery, participants then performed a TTE consisting of a standardized 5-min warm up at 100 W followed by the TTE at 70% of PPO (see details below). Upon arrival for the

2nd familiarization trial, participants practiced the TTE a total of two times, separated by 25-30 minutes.

Experimental Trials – Upon arrival participants voided their bladder and nude body mass (kg) was recorded. A urine sample was tested for urine specific gravity (PAL-10S, Atago, Japan) to determine hydration status. Participants were considered euhydrated if urine specific gravity was ≤1.020, or else the test was rescheduled (no trials were rescheduled from hypohydration). Participants were then instrumented (see below) and entered an environmental chamber and were seated on a chair. Participants then performed a 5-min baseline in thermoneutral conditions (~22.0°C, ~50% relative humidity) sitting quietly with their eyes closed. Next, participants performed one of the following 4 experimental conditions before commencing the TTE:

Thermoneutral (TN) – Participants remained seated in the chamber in a temperate environment(~22.0°C, ~50% relative humidity) for 25 minutes (30 minutes total) before commencing the TTE in the same environmental conditions. Although, endurance capacity has been demonstrated to improve in cooler temperatures (4°C and 11°C) (8), we aimed to minimize cooling of the skin in order to have a comparative control condition without a cold stimulus.

Cold Shell (CS) – Participants remained seated in the environmental chamber as the ambient temperature was incrementally decreased to 0°C (~15-16 minutes) and wind speed was increased to 0.8-1.2 m/s using a fan. Participants remained seated for an additional ~15 minutes such that cold exposure was ~30-min in duration prior to commencing the TTE. This design allowed for core temperature to remain relatively unchanged while skin/shell temperature was reduced.

HYPO-0.5°C – Participants remained seated in the environmental chamber as ambient temperature was incrementally decreased to 0°C and wind speed was increased to 0.8-1.2 m/s until the participants' rectal temperature (T_{re}) dropped by Δ-0.3°C from baseline. This design was implemented in order to target a T_{re} decrease of Δ-0.5°C at the start of the TTE with the additional time for transfer to the ergometer along with postural shifts.

HYPO-1.0°C – Participants remained seated in the environmental chamber as ambient temperature was incrementally decreased to 0°C and wind speed was increased to 0.8-1.2 m/s until the participants T_{re} dropped by Δ-0.8°C from baseline before transferring to the ergometer and performing the TTE. This design was implemented in order to target a T_{re} decrease of Δ-1.0°C for the TTE.

For all cold trials, there was an institutional ethical cutoff of core temperature ≤ 35.0°C and an exposure limit of 150-min following chamber air temperature reaching 0°C in cold trials. Three participants (30%) did not reach the desired Δ-0.8°C T_{re} within the 150 minutes cutoff limit. Each of these participants started the transition following the cutoff time with a Δ-0.7°C T_{re}. The three cold trials performed the TTE in 0°C air and ~0.5 m/s wind speed. Due to the overall challenge of core cooling in cold air, we were unable to time-match environmental exposure for all 4 conditions.

Time to Exhaustion – The TTE started with a standardized 'warmup' of 5-min at 100 W followed by the TTE at 70% of PPO. Participants freely choose their cadence, and the test was performed to volitional fatigue or when cadence dropped below 60 rpm for 5 consecutive seconds. No feedback or verbal motivation was provided except for one verbal warning if cadence dropped below 60 rpm. Due to differences in completion times between participants and trials, comparison of physiological responses were averaged over 30-s at isolated percentages (ISO) of 0%, 25%, 50%, 75%, and 100% of each completed TTE. Therefore, the ISO-timepoints compared are different based on the TTE in each condition and are different between trials.

Clothing – During TN trials, participants wore a cotton t-shirt or cycling jersey, cycling bib shorts, socks, athletic/ cycling shoes, and metabolic mask (~ 0.26 clo ensemble). In all cold trials, participants wore the same ensemble as TN at baseline with the inclusion of track pants (~0.48 clo ensemble). Upon commencement of cooling the chamber, participants were fitted with earmuffs, winter gloves, and a fleece blanket around their shoes (~0.63 clo ensemble). Prior to the TTE, the blanket was removed (~0.57 clo ensemble). The additional clothing during the cold trials was deemed necessary during pilot testing to offset extreme discomfort of extremities during cooling and minimize the risk of participant dropout.

Perceptual Measurements – Prior to performing the TTE, motivation was taken using a 0-4 scale (27), as well as shivering intensity measured by the experimenter on a 0-4 scale (0 = no shivering, 1 = occasional mild tremor of the jaw and neck, 2 = intense tremors of the chest, 3 = intermittent vigorous generalized tremor, continuous violent muscle activity)**.** Subjective assessments of the environmental conditions were assessed using a 1-4 scale to measure thermal comfort and a 1-7 scale for thermal sensation (28), and ratings of perceived exertion (6-20) (29) at ISO0% and ISO100%.

Physiological Measurements – Prior to baseline, participants self-instrumented with a flexible thermocouple (RET-1, Physitemp Instruments, USA) 15 cm beyond the anal sphincter to measure T_{re} (°C) sampled at 4 Hz. Weighted mean skin temperature ($\overline{T}_{skin}$, °C) and mean heat flux (HF, W·m^{-2}) were measured using heat flux sensors with an integrated thermistor (Concept Engineering, Old Saybrook, USA) sampled on seven sites (30):

$$\overline{T}_{skin} \text{ and HF} = 0.07_{forehead} + 0.14_{forearm} + 0.05_{hand} + 0.35_{abdomen} + 0.19_{thigh} + 0.13_{shin} + 0.07_{foot}$$

Water vapor pressure of the skin was measured using a temperature and humidity sensor (HMP60-L, Vaisala, FN) sampled at four sites: upper arm, chest, thigh, and calf. Heart rate was calculated using R-R intervals using a standard three-lead electrocardiogram (MLA2340, AD Instruments; USA). Participants were fitted with a soft silicone facemask (Hans Rudolph, USA) connected to a 4.7 L gas mixing chamber where gas volume was measured using a pneumotach (MTL 1000L, AD Instruments; USA; Pneumotach Amplifier Series 1110, Hans Rudolph Inc., USA) and gas concentrations with a gas analyzer (ML206 Gas Analyzer, AD Instruments, USA). Measures of expired ventilation ($\dot{V}_E$, L·min^{-1}), oxygen consumption ($\dot{V}O_2$, L·min^{-1}), carbon dioxide expiration ($\dot{V}CO_2$, L·min^{-1}), and respiratory exchange ratio (RER, $\dot{V}CO_2/\dot{V}O_2$) were used to calculate metabolic heat production and heat loss from the respiratory tract. In order to index workload, $\dot{V}O_2$was normalized to body mass (mL·kg·min^{-1}) during the TTE. Calculations were adjusted based on barometric pressure (mmHg) and mixing chamber air temperature (°C, sampled at 1 kHz) to account for changes in body temperature influencing gas volumes through changes in expired air temperature. The metabolic cart was calibrated following the manufacturer's instruction using air tanks containing 16% oxygen and 5% carbon dioxide.

Partitional Calorimetry Calculations – Heat storage using partitional calorimetry was calculated each minute during the thermoneutral and cooling periods prior to the TTE and normalized to body surface area using the following equation (31):

$$\dot{S} = \dot{M} - \dot{W}_K \pm \dot{R} \pm \dot{C}_{skin} \pm \dot{K} - \dot{E}_{skin} - (\dot{E}_{resp} + \dot{C}_{resp})\ [W \cdot m^{-2}]$$

Where: $\dot{S}$= heat storage, $\dot{M}$ = metabolic heat production, $\dot{W}_K$= energy used for work, $\dot{R}$ = Radiation, $\dot{C}_{skin}$ = convection of skin, $\dot{K}$= conduction, $\dot{E}_{skin}$= evaporation from skin, $\dot{E}_{resp}$= evaporation from respiratory tract, and $\dot{C}_{resp}$ = convection from respiratory tract. $\dot{W}_K$ is considered 0 in this study as participants were at rest. $\dot{K}$ is assumed to be at 0 in this experiment. Combined $\dot{R} \pm \dot{C}_{skin}$ was determined through weighted HF. One-minute averages of each component were taken from baseline and over the course of the environmental condition prior to performing the TTE.

Metabolic Heat Production – Heat production was calculated using indirect calorimetry of expired gases using the following equation if RER was < 1.00 (31)**:**

$$\dot{M} = \left(\dot{V}O_2 \cdot \frac{\left[\left(\left(\frac{RER - 0.7}{0.3}\right) \cdot 21.13\right) + \left(\left(\frac{1.0 - RER}{0.3}\right) \cdot 19.62\right)\right]}{60} \times 1000 \right) / A_D \; [W \cdot m^{-2}]$$

Where, $\dot{V}O_2$ is in L·min^{-1}, RER is the respiratory exchange ratio, and is normalized to A_D is body surface area calculated using the following equation:

$$A_D = 0.202 \times (\text{Height})^{0.425} \times (\text{mass})^{0.725} \; [m^2]$$

Where, height is in m and mass is in kg.

Indirect calorimetry assumes that metabolic heat production is due to oxidative, rather than non-oxidative (anerobic) energy sources (31), however during passive cold exposure, RER has the potential to ≥ 1 due to increased reliance on glycogen and carbohydrates to fuel shivering thermogenesis (32) and/or through increased lactate production and hyperventilation leading to increase carbon dioxide expired (33). If RER ≥ 1, the following equation was used to account for the energy equivalent for carbohydrates only (31)**:**

$$\dot{M}\,(RER \geq 1.0) = \left(\dot{V}O_2 \cdot \frac{21.13}{60} \times 1000 \right) / A_D \; [W \cdot m^{-2}]$$

Energy expenditure was calculated as Kcals expended from the start of baseline until the commencement of the TTE by taking the integral of $\dot{M}$ in W divided by 70 to convert to Kcals (22).

Evaporative heat loss from the skin surface – The following equation was used to determine $\dot{E}_{skin}$ from the relative humidity sensors and environmental factors (31, 34)**:**

$$\dot{E}_{skin} = h_e \cdot \omega \cdot (P_{skin} - P_a) \ [W \cdot m^{-2} \cdot °C]$$

Where, h_e = heat transfer coefficient for evaporative heat loss, ω = skin wittedness of participant, assumed to be minimal at 0.06 due to no regulatory sweating, P_{skin} = saturated vapor pressure of the skin, P_a = partial vapor pressure of the air.

The heat transfer coefficient for evaporative heat loss (h_e) is calculated by re-arranging the Lewis relation equation:

$$\text{Lewis Relation} = \frac{h_c}{h_e}$$

Where, the Lewis relation is assumed to be 16.5 $°C \cdot kpa^{-1}$, h_c = convective heat transfer coefficient, and h_e = heat transfer coefficient for evaporative heat loss. The convective heat transfer coefficient was calculated with the following equation (31):

$$h_c = 8.3v^{0.6} \ [W \cdot m^2 \cdot K^{-1}]$$

Where v is air velocity in $m \cdot s^{-1}$. This equation is used for air velocities between 0.2-4.0 $m \cdot s^{-1}$. Wind speed was recorded using a handheld anemometer (Kestrel 1000, ITM Instruments, CAN) for convective heat loss at the level of xyphoid process of the participants at baseline and every 15-min.

Saturated vapor pressure of the skin was calculated using Antoine’s equation by using mean skin temperature:

$$P_{skin} = \frac{\exp\left(18.956 - \frac{4030.18}{\overline{T}_{skin} + 235}\right)}{10} \text{ [kpa]}$$

Where, $\overline{T}_{skin}$ = mean skin temperature (°C), division by 10 is to convert P_{skin} from mb to kPa.

The partial vapor pressure in the air (P_a) and saturated vapor pressure of water (P_{sa}) were derived based on their relationship with relative humidity (∅, fractional %) using temperature and humidity measurements from sensors with the following equations:

$$P_a = \emptyset P_{sa} \text{ [kPa]}$$

Saturated vapor pressure at the skin was calculated for each site, then weighted using the following equation which was originally derived for mean skin temperature (35):

$$\text{Weighted Relative Humidity or } T_{amb\ skin} = 0.3_{arm} + 0.3_{chest} + 0.2_{thigh} + 0.2_{calf}$$

Respiratory Heat Loss – Combined convective and evaporative heat loss from the respiratory tract was the summation of the following equations (31)**:**

$$\dot{C}_{resp} = \frac{\left(0.001516 \cdot \dot{M}\left(28.56 + (0.641 \cdot P_{a\ air}) - (0.885 \cdot T_{amb})\right)\right)}{A_D} \text{ [W} \cdot \text{m}^2\text{]}$$

$$\dot{E}_{resp} = \frac{\left(0.00127 \cdot \dot{M}\left(59.34 + (0.53 \cdot P_{a\ air}) - (11.63 \cdot T_{amb})\right)\right)}{A_D} \text{ [W} \cdot \text{m}^2\text{]}$$

Where $\dot{M}$ is in W, $P_{a\ air}$ is the vapor pressure of inspired air in kPa, and T_{amb} is ambient temperature of inspired air in °C. Ambient temperature (T_{amb}, °C) and relative humidity (%) were measured using a hand-held hygrometer and thermometer (Pocket DewPoint, VWR, USA) for respiratory heat loss at the level of xyphoid process of the participants at baseline and every 15-min.

Heat Debt - The change in body heat content over time or HD was obtained by taking the integral of heat storage and converting to kJ with the following equation (23, 31)**:**

$$\Delta HD = \int_{t=0}^{t} \dot{S} * A_D * dt/1000 \; [kJ]$$

Where, the rate of heat storage is converted to W by multiplying by A_D, then multiplied by exposure time (dt) in seconds (s) and divided by 1000 to convert W to kJ. HD was calculated every minute from when cooling the chamber started until prior to commencing the TTE.

Statistical Analysis – All physiological data are presented as mean ± SD with statistical significance set a $p \leq 0.05$. All data analyses of physiological variables were conducted in R (version 4.2.2) using the RStudio environment (Version 2023.03.1.446) (36). Data were analyzed using a linear mixed model (lmer) with a fixed effect for condition and timepoint (if necessary) and random effect for participant using the R package l*me4* (37). Data were normally distributed determined through visual inspection of Q-Q plots and using the Shapiro-Wilks test (in *car* package) (38). Homoscedasticity was confirmed through visual inspection of the residuals plotted over the fitted linear mixed model and using a Levine's test for homogeneity of variance (in *car* package) (38). Three types of linear mixed models were performed (depending on variable) including; a 1 x 4 condition (TN vs CS vs HYPO-0.5°C HYPO-1.0°C), or a 4 (condition) x 6 (timepoint; Baseline vs ISO0% vs ISO25% vs ISO50% vs ISO75% vs ISO100%), or a 4 (condition) x 5 (timepoint; ISO0% vs ISO25% vs ISO50% vs ISO75% vs ISO100%). A repeated measures ANOVA was performed on each linear mixed model, when significant ($p \leq 0.05$), a Bonferroni *post hoc* analysis corrected for multiple comparisons was used to test for specific main effects between conditions and timepoints using the *emmeans* package (39). If there was a significant interaction ($p \leq 0.05$), a 1 x 4 condition Bonferroni *post hoc* analysis performed at each specific timepoint to compare differences between conditions. Cohen's *d* (40) was used to calculate effect sizes for TTE data between conditions where descriptors of magnitude (41) are very small 0.01, small 0.2, medium 0.5, large 0.8, and very large 1.2.

Perceptual data (RPE, TC, TS) were analyzed using 4 (condition) x 2 ISO-timepoint (ISO0%, ISO100%) repeated measures ANOVAs. As data was not normally distributed and ordinal data, post hoc comparisons between conditions were also performed using a Wilcoxon-Signed Rank test at ISO0% and ISO100%. Motivation and shivering intensity were assessed using a 1 x 4 (condition) Friedman's ANOVA with a Wilcoxon-Signed Rank test for post-hoc analysis to compare between conditions. To reduce the likelihood of Type 1 error due to multiple comparisons, α value was revised based on number of comparisons (total 6), therefore $p \leq 0.008$ was set for significance. All perceptual analyses are expressed as median (quartile 1 – quartile 3) and were performed using SPSS statistics for Windows.

Results

Thermal Manipulations – Cooling times prior to performing the TTE were as follows: CS (30.0 ± 1.1 min), HYPO-0.5°C (116.0 ± 39.2 min) and HYPO-1.0°C (160.3 ± 32.3 min). We were successful at creating a CS group (neutral core, cooled skin/shell) and two mild hypothermia groups (reduced T_{re} and cold skin) compared to TN. There was a significant condition, timepoint, and interaction effect (all $p < 0.001$) for T_{re} (Figure 1A), relative ΔT_{re} (Figure, 1B) and $\overline{T}_{skin}$ (Figure 1C) where pairwise comparisons demonstrated no difference at Baseline for each variable (all $p = 1.00$). For absolute T_{re}, at ISO0%, both TN and CS were significantly different (both $p < 0.001$) from HYPO-1.0°C that was maintained throughout the TTE. There were significant differences (all $p < 0.02$) between TN and CS compared to HYPO-0.5°C from ISO25% to the end of the TTE. Relative ΔT_{re} was significantly lower in HYPO-0.5°C and HYPO-1.0°C compared to TN (all $p \leq 0.004$) and CS (all $p \leq 0.001$) at all TTE ISO timepoints. Mean skin temperature was significantly lower than TN at all TTE ISO timepoints in CS, HYPO-0.5°C, and HYPO-1.0°C (all $p \leq 0.001$). Furthermore, HYPO-0.5°C, and HYPO-1.0°C was significantly lower (all $p \leq 0.01$) compared to CS at all TTE ISO timepoints with no difference between HYPO-0.5°C, and HYPO-1.0°C (all $p > 0.05$).

[Insert Figure 1 About Here]

Partitional Calorimetry – There was a significant condition effect (all $p \leq 0.018$) for $\dot{M}$ (Figure 2A), $\dot{R} \pm \dot{C}_{skin}$ (Figure 2B), $\dot{E}_{resp} + \dot{C}_{resp}$ (Figure 2C), $\dot{E}_{skin}$ (Figure 2D), $\dot{S}$ (Figure 2E), and HD (Figure 2F). Metabolic heat production (all $p \leq 0.033$) was significantly higher in all cooling conditions compared to TN, with $\dot{M}$ significantly greater in HYPO-0.5°C and HYPO-1.0°C compared to CS. Radiative and convective heat loss from the skin was significantly (all $p \leq 0.001$) greater in all cold conditions compared to TN, with no differences (all $p = 1.000$) between the cold conditions. Respiratory heat loss increased with cooling where each condition was significantly different from each other (all $p \leq 0.031$). Evaporative heat loss increased with cooling (~2-3 $W{\cdot}m^2$), however was only significantly different ($p = 0.007$) between TN and CS only and approached significance between TN and HYPO-0.5°C ($p = 0.055$) and HYPO-1.0°C ($p = 0.055$). Heat storage was significantly (all $p \leq 0.018$) reduced compared to TN (-23.4 ± 12.9 $W{\cdot}m^2$) in all cooling conditions. Heat storage was significantly (both $p \leq 0.001$) lower in CS (-87.0 ± 13.6 $W{\cdot}m^2$) compared to HYPO-0.5°C (-54.0 ± 17.9 $W{\cdot}m^2$) and HYPO-1.0°C (-41.0 ±

12.6 W·m[2]). The was a significant condition effect ($\eta_p^2 = 0.76$, $p < 0.001$) where heat debt was greater in HYPO-1.0°C (-808.0 ± 371.0 kJ), HYPO-0.5°C (-734.0 ± 294.1 kJ), compared to TN (-129.0 ± 71.2 kJ, both $p < 0.001$). There were no differences in heat debt between CS (-328.0 ± 65.2 kJ) and TN ($p = 0.172$). Both HYPO-0.5°C ($p = 0.005$) and HYPO-1.0°C ($p = 0.009$) were lower compared to CS. There were no differences between HYPO-0.5°C and HYPO-1.0°C for any variable used to calculate $\dot{S}$ and HD (except for $\dot{E}_{resp} + \dot{C}_{resp}$). For Kcals expended, there was a significant condition effect ($p \leq 0.001$), where the number of Kcals expended were not different between TN (64.0 ± 11.2 kcals) and CS (72.4 ± 6.2 kcals) ($p = 1.00$), but were significantly increased in both HYPO-0.5°C (387.0 ± 153.9 kcals) and HYPO-1.0°C (576.0 ± 151.0 kcals) compared to TN and CS (all $p \leq 0.001$. Participants expended more calories in HYPO-1.0°C compared to HYPO-0.5°C ($p = 0.001$). In order to express relative shivering intensity, % $\dot{V}O_{2\ peak}$ was calculated from the final 10 minutes of each cooling period. There was a significant condition effect ($p \leq 0.001$) where all 3 cold conditions (CS: 14.0 ± 2.5% $\dot{V}O_{2\ peak}$, HYPO-0.5°C: 19.1 ± 3.9% $\dot{V}O_{2\ peak}$, HYPO-1.0°C: 20.9 ± 3.3% $\dot{V}O_{2\ peak}$) were significantly higher than TN (10.7 ± 1.8% $\dot{V}O_{2\ peak}$; all $p < 0.05$) and both core cooling conditions were higher than CS (both $p < 0.001$), but not different from each other.

[Insert Figure 2 About Here]

Cardiorespiratory and Cadence Responses – Data for heart rate is reduced to $n = 9$ due to poor signal quality. There was a significant condition, timepoint, and interaction (all $p < 0.001$) for heart rate (Figure 3A) and $\dot{V}O_2$ (Figure 3B). Pairwise comparisons demonstrated a non-uniform difference of responses between conditions, where significant differences ($p < 0.05$) are displayed in Figure 3A and 3B. There was a significant timepoint effect ($p < 0.001$), but no condition ($p = 0.074$) or interaction ($p = 0.970$) for cadence, where cadence declined over the course of the TTE and was lower in ISO100% (all $p < 0.05$) compared to all other ISO timepoints (Figure 3C).

[Insert Figure 3 About Here]

Perceptual Variables – There was a significant condition, and interaction (all $p < 0.05$) for RPE, TS, and TC (Table 2). There was a significant iso-timepoint effect (both $p < 0.05$), where RPE and TS increased over the course of the TTE. However, there was no condition effect for TC ($p = 0.399$). Post-hoc comparisons are displayed in Table 2. RPE was significantly higher at ISO0% in HYPO-1.0°C compared to TN, with no differences at ISO100% between conditions. Thermal sensation was lower in all cold conditions compared to TN at ISO0% (all $p < 0.007$), while TS remained lower at ISO100% in both core cooling conditions compared to TN and CS (all $p < 0.007$). Thermal comfort was higher (i.e., more uncomfortable) in both core cooling conditions compared to TN (both $p = 0.004$) at ISO0%. Thermal comfort approached significance between TN and CS ($p = 0.013$) and CS and HYPO-0.05°C ($p = 0.020$) at ISO0%, with no differences between (all $p > 0.007$) at ISO100%. There was a significant condition effect ($p < 0.001$) for shivering intensity where shivering was higher in the two core cooling conditions, with no differences between TN and CS ($p = 0.062$, Table 2). There was a significant condition effect ($p \leq 0.001$) for motivation to perform TTE, however post-hoc comparisons determined there were no difference between conditions (all $p \geq 0.011$) (Table 2).

[Insert Table 2 About Here]

Endurance Capacity - There was a significant condition effect ($p \leq 0.001$, partial eta$^2 = 0.66$) for TTE (Figure 4A) where endurance capacity decreased from TN (23.75 ± 13.75 min) in

HYPO-0.5°C (8.46 ± 5.23 min, Δ-61.4 ± 19.7%, $p \leq 0.001$, $d = 1.27$), and HYPO-1.0°C (6.46 ± 5.60 min, Δ-71.6 ± 16.4%, $p \leq 0.001$, $d = 1.44$), and approached significance in CS (16.22 ± 10.30, Δ-30.9 ± 21.5%, $p = 0.055$, $d = 0.61$). Furthermore, participants had a greater endurance capacity in CS compared to HYPO-0.5°C ($p = 0.045$, $d = 0.87$), and HYPO-1.0°C ($p = 0.007$, $d = 1.09$), with no differences between HYPO-0.5°C and HYPO-1.0°C ($p = 1.00$, $d = 0.22$). When TTE is expressed as a % change from TN (Figure 4B), there was a significant condition effect ($p \leq 0.001$) with a decrease (all $p \leq 0.001$) in CS (Δ-30.9 ± 21.5%), HYPO-0.5°C (Δ-61.4 ± 19.7%), HYPO-1.0°C (Δ-71.6 ± 16.4%). Both core cooling conditions had greater impairment compared to CS (both $p \leq 0.001$), with no differences between the two core cooling conditions ($p = 0.721$). The average peak afterdrop in T_{re} over the course of the TTE were: TN (0.0 ± 0.1°C), CS (0.1 ± 0.1°C), HYPO-0.5°C (0.2 ± 0.2°C), HYPO-1.0°C (0.3 ± 0.2°C).

[Insert Figure 4 About Here]

Discussion

In real-life scenarios such as acute exposure or survival situations in the cold, the first experience faced by an individual is a reduction in skin temperature, occurring well before significant changes to core temperature. If cold exposure continues, eventually core temperature drops along with further skin cooling. Therefore, we aimed to determine if there was a dose-response of cold exposure on endurance capacity in cold (0°C) air; this was done by separating and isolating the effects of a cold outer shell - without changes in core temperature - compared to two levels of core cooling. Our first hypothesis was accepted as cooling just the shell by itself without any core cooling was sufficient to increase physiological strain and caused a medium to large reduction in endurance capacity by ~30% compared to thermoneutral. Our second hypothesis was accepted as mild cooling of the core led to a very large impairment in capacity with a further ~30-40% reduction compared to skin cooling alone. Our third hypothesis was rejected as there were no differences between the two core cooling conditions. While we attempted to have two distinct doses of core cooling, the drop in core temperature and actual heat debt incurred were similar, and this may have contributed to the similar endurance capacity.

Consensus for whether cold air by itself impairs exercise capacity is equivocal (20), as most studies initiate exercise directly upon cold exposure. Thus, actual skin cooling and heat debt is minimized and offset by the large and immediate endogenous metabolic heat production from exercise. In the CS condition of the current study, participants were exposed to cold air for ~30 minutes before initiating the TTE, inducing redistribution of peripheral blood to core, as well as significant reductions in $\overline{T}_{skin}$ (~-7.6°C), and likely superficial muscle temperature (Quad skin temperature of 23.1 ± 2.1 °C in CS versus 28.9 ± 1.1 °C in TN at ISO0%). Even though core temperature did not significantly decrease, heat debt decreased ~200 kJ more than thermoneutral, suggesting that cooling did occur. Furthermore, the rate of heat storage ($\dot{S}$) was the lowest of all three cooling conditions, as there was a large decrease in $\overline{T}_{skin}$ with initial cold exposure (due to vasoconstriction and $\dot{R} \pm \dot{C}_{skin}$ heat loss) compared to a relatively minor increase in shivering thermogenesis ($\dot{M}$) (42). Overall, there was a significant reduction in TTE time by ~31% indicating CS alone and exercising in inadequate clothing can limit overall endurance capacity in cold air. Impairment was not uniform, with a wide range of responses from -64% for one participant to another improving performance by +6%, however, these two individuals were 2/3 lowest TTEs in TN, which may explain their variability in this condition. There was likely strong vasoconstriction with our average $\overline{T}_{skin}$ of ~25.2˚C at ISO0%, as maximal vasoconstriction occurs at $\overline{T}_{skin}$ of ~29.5-30˚C (32). This likely impaired performance through decreased blood flow to working muscles and superficial muscle cooling. For example, it has previously been reported that 15-min of 12°C cold-water leg immersion decreased maximal power (13.7%) and average power (9.5%) during a 30-s cycling sprint in thermoneutral conditions (43). Our data thus highlight the importance of preventing shell cooling, supported by observations that wearing a heated vest for 25-min of rest in cold air (8°C) prevented core and skin temperature decreases compared to wearing a tracksuit, eliciting a ~1.1% improvement in subsequent rowing time trial performance (17). Together, these results indicate that skin/shell cooling by itself combined with inadequate clothing can impair endurance capacity in cold air, though the magnitude of this response may vary widely across individuals.

With continued cold exposure, core cooling itself can occur and may further negatively impact exercise capacity. In the current study, core cooling led to a large impairment in endurance capacity beyond just cooling the shell alone. The overall absolute magnitude of core temperature cooling was relatively small (ranged 35.6°C to 36.9°C at ISO0% in HYPO-1.0°C) which is above clinical hypothermia (≤ 35°C core temperature) and in some individuals within a normothermic range. However, it is clear that individuals were cold strained as relative to TN and CS, both core cooling conditions induced significant reductions in $\overline{T}_{skin}$, relative T_{re}, and thermal discomfort, increased shivering, along with prolonged negative heat storage and greater heat debt prior to exercise. Pre-exercise shivering – measured as average $\dot{M}$ in the partitional calorimetry calculations – was about two-fold greater in both core cooling conditions than in TN or CS. At the end of the cooling periods, the relative intensity of $\dot{M}$ was ~19% and 21% of peak oxygen consumption in HYPO-0.5°C and HYPO-1.0°C, respectively, compared to ~10% in TN. Thus, one potential mechanism for impairment may be reduced motor coordination or altered motor unit recruitment strategies within musculature from the asynchronous shivering contractions. Shivering primarily occurs in trunk and thigh muscles where continuous low intensity shivering (~2-5% maximal voluntary contraction) recruit primarily Type I muscle fibers, while high intensity bursts (~7-15% of maximal voluntary contraction) recruit Type II muscle fibers (For review see: (44)) and were very likely similar muscle types required for our submaximal test workload. Further, local cooling of muscles decreased maximal voluntary force while altering motor unit contractile characteristics and recruitment patterns (7). Collectively, the pre-exercise shivering may have impaired endurance capacity through a direct influence on muscle capacity. However, future studies are needed measuring muscle temperature, muscle activity/recruitment (e.g., using electromyography), or biomechanical analyses of the pedal stroke to fully elucidate this mechanism. Beyond colder muscles alone or changes in motor coordination from shivering, another mechanism of impairment may be a competition between metabolic demands of exercise itself versus that from shivering. Comparing pre-cooling to a sustained 40% of peak shivering versus no pre-cooling, Gagnon et al. (3) reported a reduction in treadmill speed in order to maintain a constant metabolic demand of either light or moderate exercise intensities of 50 or 70% peak oxygen uptake, respectively. In both Gagnon et al. (3) and the current study, endogenous heat production from exercise appears insufficient to compensate for the large heat debt, and shivering throughout subsequent exercise likely contributed to further decreases in exercise capacity in both core cooling conditions compared to the cold shell condition. Lastly, another potential mechanism for impaired performance with core cooling is decreased oxygen availability caused by a reduction in muscle blood flow and oxygen diffusion due to a leftward shift of the oxygen disassociation curve (1, 2, 14). We have previously determined that the use of hyperoxia (40% oxygen) can counter declines in 15 km cycling time-trial performance in cold air with a 0.5°C reduction in core temperature. However, it is currently unknown if manipulation of oxygen availability can also influence endurance capacity in the cold (1).

Our previous study reported an approximate 6% reduction in average wattage in 15 km cycling time trial performance with a 0.5°C decrease in core temperature (1), and we aimed to extend this range with a dose response of core cooling. Across a range of core cooling, Bergh and Ekblom (15) reported a 20%·°C^{-1} linear reduction in maximal work time below a threshold esophageal and muscle temperature of 37.5°C and 38°C, respectively through to absolute core temperature reductions to ~35°C. We extend their findings by demonstrating an average reduction of TTE by 72% with a 1°C decrease in core temperature. However, we did not find a similar linear decrease with core temperature. Despite our pre-experimental target of a 0.5°C T_{re} difference between the two core cooling conditions, there was no statistical significance in HD at the end of cooling, nor in core temperature or skin temperature at ISO0%. The lack of HD differences may be due to continued core cooling increasing shivering drive, as $\dot{M}$ progressively increases and is near maximal at a core temperature of ~35°C (45), while reductions in $\overline{T}_{skin}$ decreases the thermal gradient between the skin and environment reducing convective heat loss during prolonged cooling (34). Though these individual partitional calorimetry components averaged over the cooling period were non-significant in our calculations, they may still have been sufficient to moderate any heat storage differences and slow down the further accumulation of HD between the two core cooling conditions in the later portion of the cooling period. The use of partitional calorimetry was advantageous in the study beyond thermometry measures to index cold strain, as HD and TTE impairment was similar between the core cooling conditions, indicating that the amount of cold accumulated prior to exercise influenced exercise capacity as opposed to cooling time per say (38% longer in HYPO-1.0°C compared to HYPO-0.5°C). More research is needed on testing partitional calorimetry tools and calculations as a majority of research occurs in hot environments (31) to provide a better understanding of heat balance in the cold.

There are several considerations and limitations in the current study limiting the understanding of cold on performance. Peak power output was determined with an incremental step protocol as opposed to an incremental ramp protocol where peak power output may have been underestimated (46). Furthermore, we did not calculate critical power or functional threshold power for our participants. This information would be valuable in determining which intensity threshold individuals were cycling in and could aid in explaining the wide inter-individual variability in TTE. Future work is needed to determine how endurance capacity at different exercise intensity is affected by cold stress, where potential lower intensity exercise is less affected and may better increase core temperature following cooling (47). Data collection was performed over the winter and spring months (November to May), where potential cold acclimation may have influenced cooling responses, however, based on participants' activity history is unlikely that they were cold acclimated. Any potential cold acclimation may not significantly impacted exercise performance, as recently Jones et al. (10) found that cold acclimation following 7 days of cold-water immersion (controlled by time and change in core temperature) did not mitigate the decrements in 20-min self-paced time-trial performance in thermoneutral conditions induced by a reduction in core temperature by ~Δ-1.5°C. We demonstrated an average T_{re} afterdrop of Δ-0.2-0.3°C during the TTEs in the core cooling conditions likely caused from the skeletal muscle pump moving cooler blood from the periphery to the core and warmer blood from the core towards the working muscle (20, 34). However, there is potential that the afterdrop was underestimated, where esophogeal temperature would be more accurate representation of organ temperature and can better respond to changes in core temperature compared to rectal temperature (48). The cardiovascular fluid shift is challenging to model (34) and we cannot account for if this shift caused an independent effect on TTE performance (e.g., through systemic vasoconstriction, decreased brain temperature). Furthermore, no blood measures were collected in this study, and it is unknown how plasma glucose and lactate levels changed in response to the cooling protocols that may have influenced TTE performance. Lastly, this study is limited to males as no females were used in the current study to control against fluctuations in resting core temperature during the menstrual cycle. On average, females have a lower body mass, height, body surface area, and greater body fat percentage compared to males and have a higher core temperature during the luteal phase that may influence cutaneous vasoconstriction, shivering and non-shivering thermogenesis (49) leading to potential sex-related differences in cooling times. However, based on the current study, regardless of cooling time or starting core temperature, core cooling impaired endurance capacity, potentially indicating that these sex-related differences may not influence endurance impairment. However, future research is needed to determine sex-related differences and if the menstrual cycle influences whole-body cooling and endurance capacity in the cold.

In summary, we determined a dose-response for cooling and endurance capacity where cooling of the shell reduced mean endurance capacity by ~30% compared to thermoneutral, and core cooling further reduced capacity by and additional ~30-40%. From an applied perspective, these data give insight into the magnitude of impairment from cold that may be useful for modeling work capacity or survival and indicate that individuals should prevent declines in shell and/or core temperature prior to performing sustained work or exercise in the cold. Furthermore, impairments in endurance capacity occur with relatively mild core cooling, well before individuals reach clinical hypothermia (core temperature ≤ 35°C). Future research is needed to investigate the high inter-individual variability in both cooling response and exercise tolerance. The current results improve our understanding of exercise responses in the cold and may help develop effective countermeasures to improve exercise and capacity in the cold.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

All authors contributed to the conception and design of the research study; PJW, JGN, JL, and NS piloted and performed the experiments. PJW and GLH performed the statistical analysis. All authors interpreted the results of the study. PJW and SSC drafted the manuscript. All authors edited, revised, and approved the final version of the manuscript.

List of Figures

Figure 1 - Thermoregulatory responses for absolute rectal temperature (Panel A), delta rectal temperature (Panel B), and mean skin temperature (Panel C) at baseline and isolated percent completion points (ISO) of the TTE (all *n* = 10 males). All data presented as mean ± SD. Each variable was analyzed using a 6 Time X 4 Condition linear mixed model repeated measures ANOVA. All variables demonstrated a significant interaction where pairwise comparisons can be interpreted as a = difference between TN and CS, b = difference between TN and HYPO-0.5°C, c = difference between TN and HYPO-1.0°C, d = difference between CS and HYPO-0.5°C, e = difference between CS and HYPO-1.0°C, f = difference between HYPO-0.5°C and HYPO-1.0°C. Legend: TN = thermoneutral, CS = Cold Skin/Shell, HYPO-0.5°C = mild core cooling (hypothermia) of Δ-0.5°C from baseline, HYPO-1.0°C = mild core cooling (hypothermia) of Δ-1.0°C from baseline.

Figure 2 – Average metabolic heat production (Panel A), average radiative and convective heat loss from skin (Panel B), average combined convective and average evaporative heat loss from respiratory tract (Panel C), average evaporative heat loss from skin (Panel D), average heat storage (Panel E) and cumulative heat debt (Panel F) over the cooling period prior to the time-to-exhaustion- test of the 4 experimental trials (all *n* = 10 males). The bar data are presented as mean ± SD, while individual values are plotted with a unique symbol for each participant consistent between figures. Each variable was analyzed using a 1 X 4 Condition linear mixed model repeated measures ANOVA. There was a significant condition effect, where pairwise comparisons can be interpreted as: TN = different from TN, CS = different from CS, HYPO-0.5°C = different from HYPO-0.5°C and HYPO-1.0°C = HYPO-1.0°C. Legend: TN = thermoneutral, CS = Cold Skin/Shell, HYPO-0.5°C = mild core cooling (hypothermia) of Δ-0.5°C from baseline, HYPO-1.0°C = mild core cooling (hypothermia) of Δ-1.0°C from baseline.

Figure 3 – Cardiorespiratory responses for heart rate (Panel A, *n* = 9 males), oxygen consumption (Panel B, *n* = 10 males) and cadence (Panel C, *n* = 10 males). All data presented as mean ± SD. Each variable was tested with a 5 Time X 4 Condition linear mixed model repeated measures ANOVA. If a significant interaction occurred, pairwise comparisons can be interpreted as a = difference between TN and CS, b = difference between TN and HYPO-0.5°C, c = difference between TN and HYPO-1.0°C, d = difference between CS and HYPO-0.5°C, e = difference between CS and HYPO-1.0°C, f = difference between HYPO-0.5°C and HYPO-1.0°C. If a significant time effect occurred, pairwise comparisons can be interpreted as: 1 = different from ISO0%, 2 = different from ISO25%, 3 = different from ISO50%, 4 = different from ISO75%, and 5 different from ISO100%. Legend: TN = thermoneutral, CS = Cold Skin/Shell, HYPO-0.5°C = mild core cooling (hypothermia) of Δ-0.5°C from baseline, HYPO-1.0°C = mild core cooling (hypothermia) of Δ-1.0°C from baseline.

Figure 4 – Time to exhaustion (Panel A) and % change in TTE (Panel B) over the 4 experimental conditions (both *n* = 10 males). The bar data are presented as mean ± SD, while individual values are plotted with a unique symbol for each participant consistent between figures. Each variable was analyzed using a 1 X 4 Condition linear mixed model repeated measures ANOVA. There was a significant condition effect for both variables, where pairwise comparisons can be interpreted as: TN = different from TN, CS = different from CS, HYPO-0.5°C = different from HYPO-0.5°C and HYPO-1.0°C = HYPO-1.0°C. Legend: TN =

thermoneutral, CS = Cold Skin/Shell, HYPO-0.5°C = mild core cooling (hypothermia) of Δ-0.5°C from baseline, HYPO-1.0°C = mild core cooling (hypothermia) of Δ-1.0°C from baseline.

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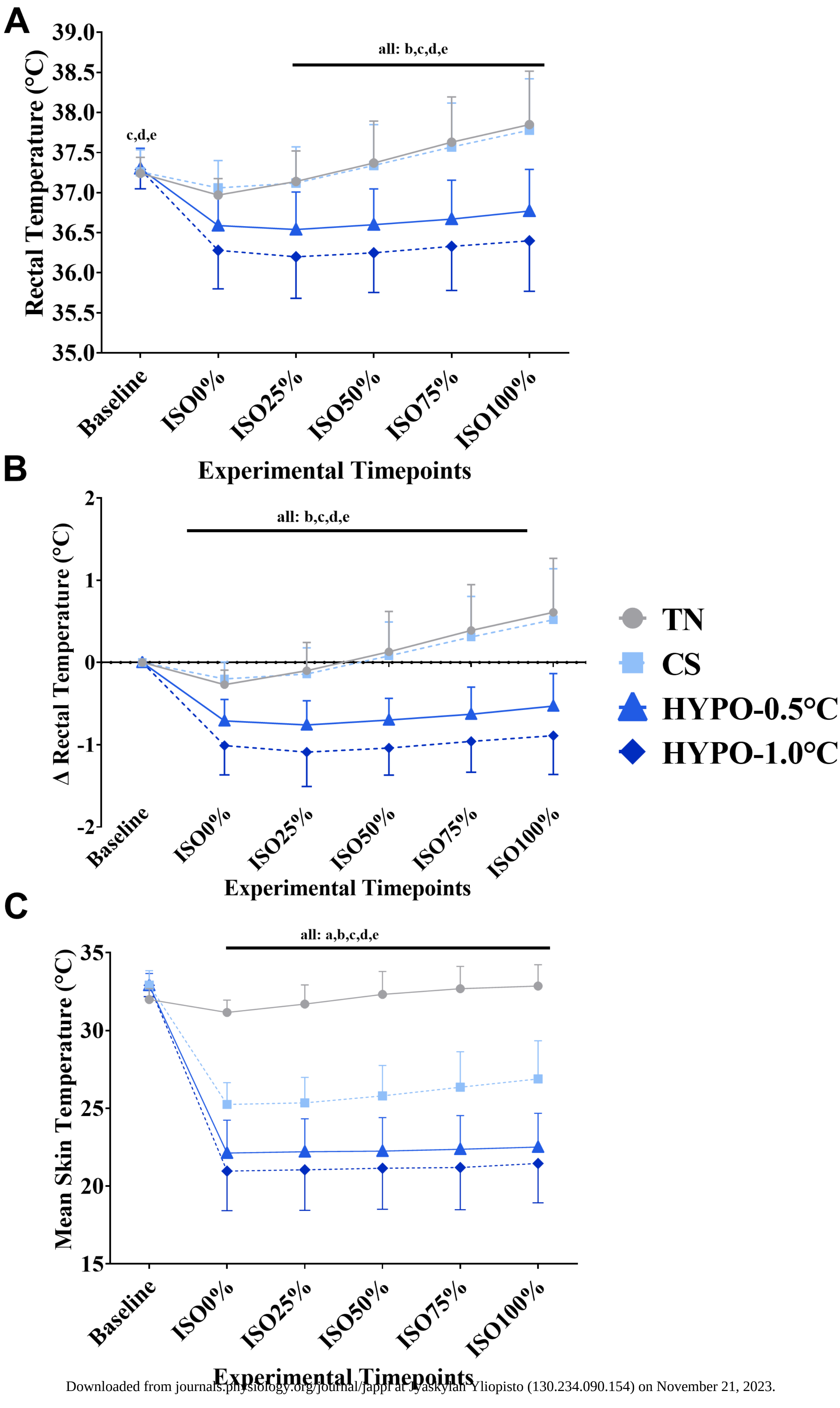
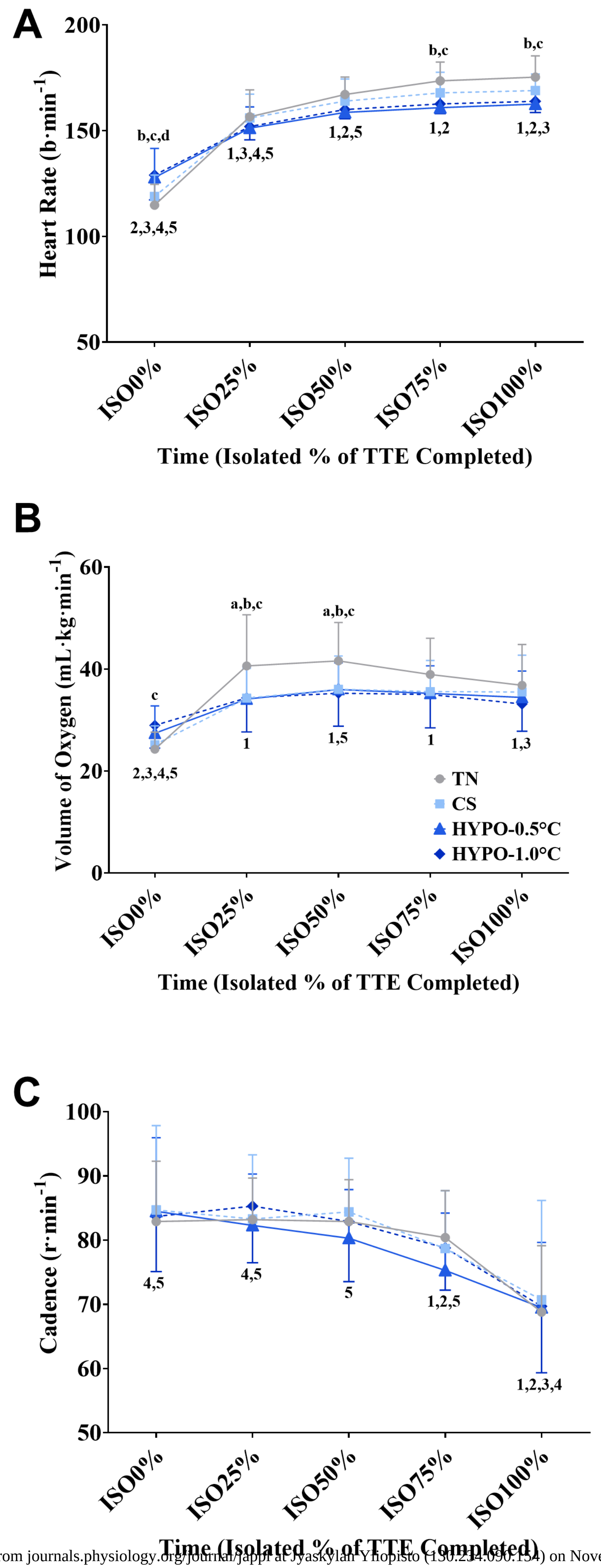
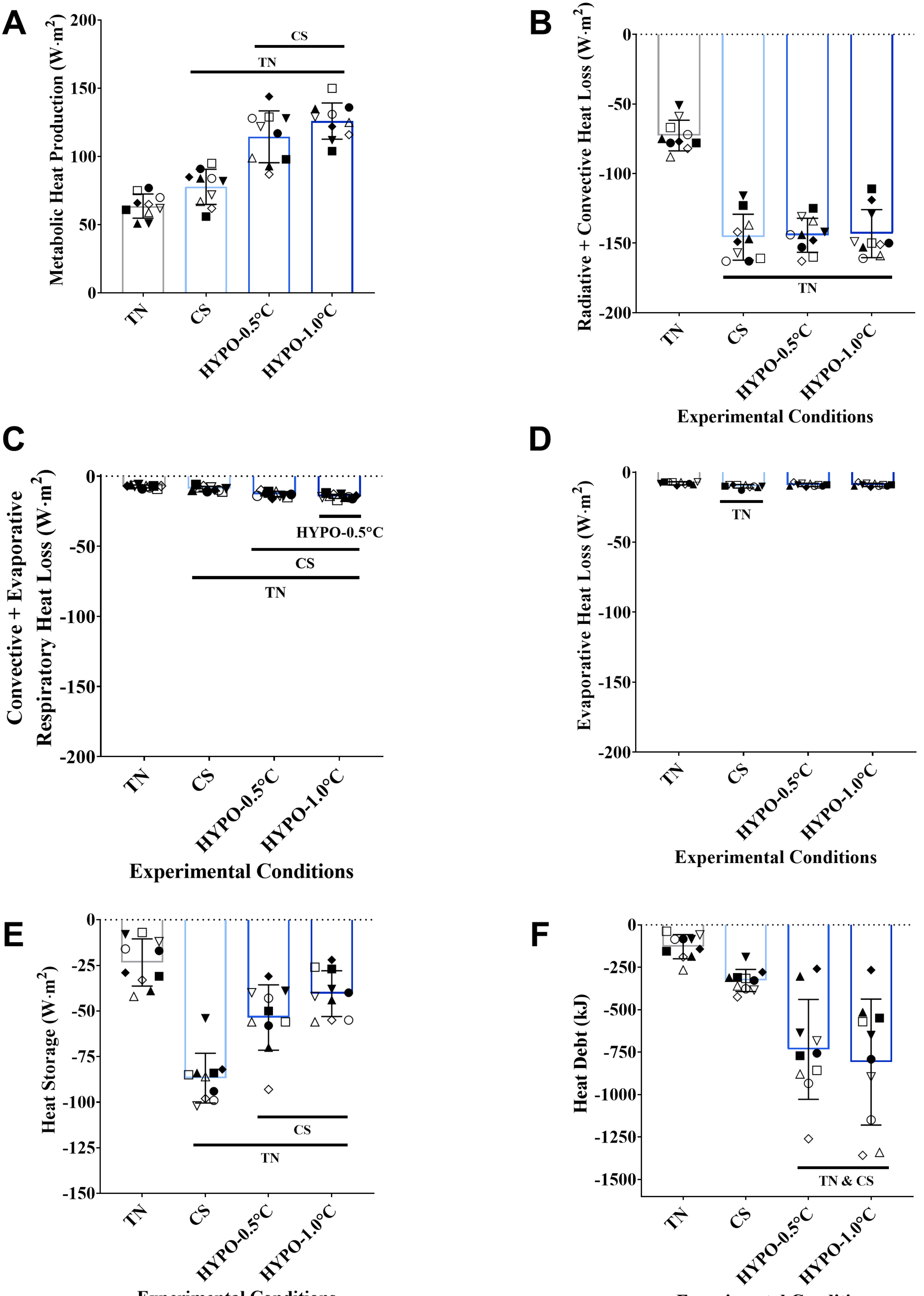
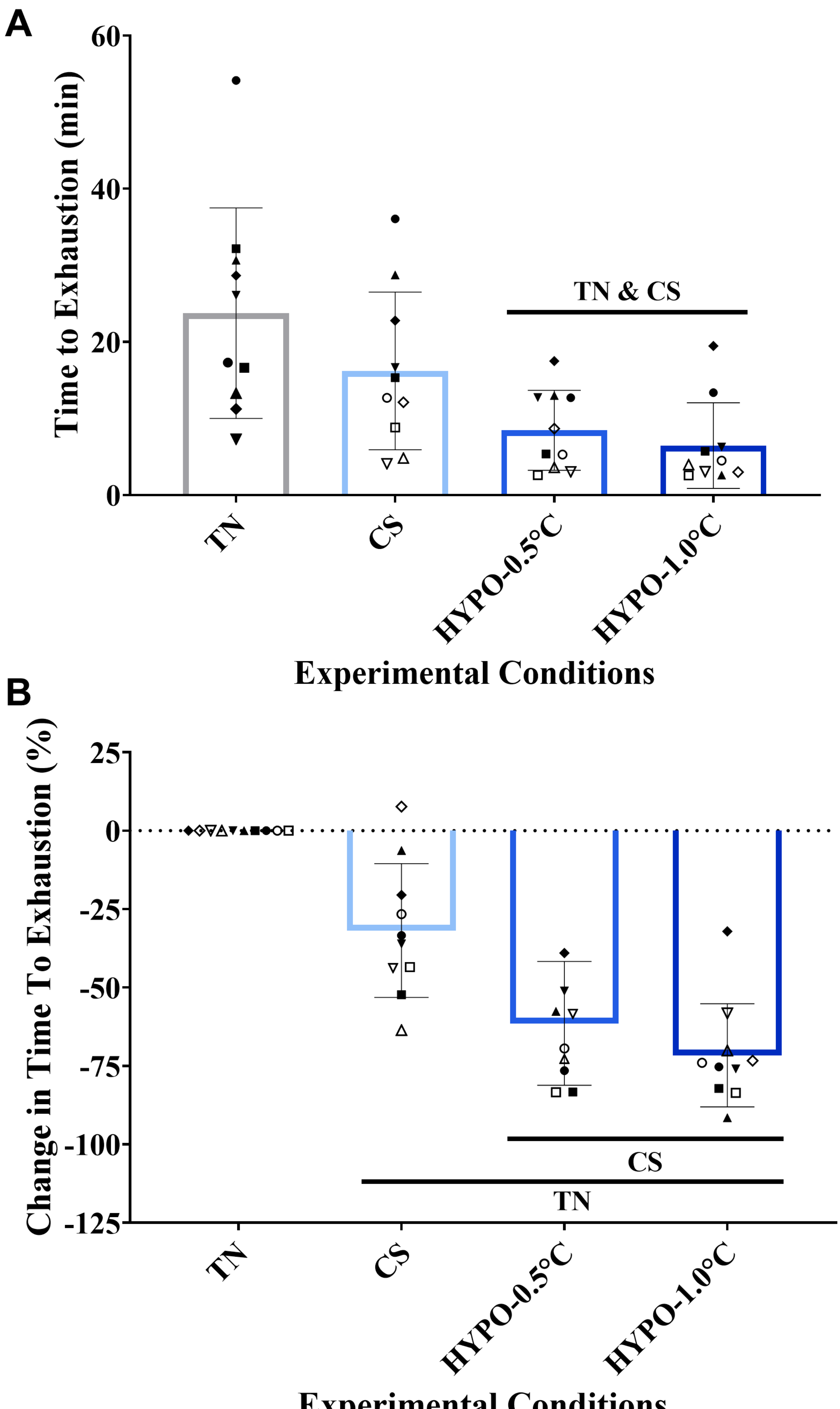

A
all: b,c,d,e
c,d,e
Rectal Temperature (°C)
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
Baseline
ISO0%
ISO25%
ISO50%
ISO75%
ISO100%
Experimental Timepoints
B
all: b,c,d,e
Δ Rectal Temperature (°C)
2
1
0
-1
-2
Baseline
ISO0%
ISO25%
ISO50%
ISO75%
ISO100%
Experimental Timepoints
TN
CS
HYPO-0.5°C
HYPO-1.0°C
C
all: a,b,c,d,e
Mean Skin Temperature (°C)
35
30
25
20
15
Baseline
ISO0%
ISO25%
ISO50%
ISO75%
ISO100%
Experimental Timepoints


A
Heart Rate (b·min-1)
200
150
100
50
b,c,d
2,3,4,5
1,3,4,5
1,2,5
b,c
1,2
b,c
1,2,3
ISO0%
ISO25%
ISO50%
ISO75%
ISO100%
Time (Isolated % of TTE Completed)
B
Volume of Oxygen (mL·kg·min-1)
60
40
20
0
c
2,3,4,5
a,b,c
1
a,b,c
1,5
1
1,3
TN
CS
HYPO-0.5°C
HYPO-1.0°C
ISO0%
ISO25%
ISO50%
ISO75%
ISO100%
Time (Isolated % of TTE Completed)
C
Cadence (r·min-1)
100
90
80
70
60
50
4,5
4,5
5
1,2,5
1,2,3,4
ISO0%
ISO25%
ISO50%
ISO75%
ISO100%
Time (Isolated % of TTE Completed)


A
Metabolic Heat Production (W·m2)
200
150
100
50
0
CS
TN
TN
CS
HYPO-0.5°C
HYPO-1.0°C
B
Radiative + Convective Heat Loss (W·m2)
0
-50
-100
-150
-200
TN
Experimental Conditions
C
Convective + Evaporative Respiratory Heat Loss (W·m2)
HYPO-0.5°C
CS
TN
-50
-100
-150
-200
D
Evaporative Heat Loss (W·m2)
E
Heat Storage (W·m2)
-25
-75
-125
F
Heat Debt (kJ)
-250
-500
-750
-1000
-1250
-1500
TN & CS


A
Time to Exhaustion (min)
60
40
20
0
TN & CS
TN
CS
HYPO-0.5°C
HYPO-1.0°C
Experimental Conditions
B
Change in Time To Exhaustion (%)
25
0
-25
-50
-75
-100
-125
CS
TN
TN
CS
HYPO-0.5°C
HYPO-1.0°C
Experimental Conditions

Variable	Mean ± SD
Age (years)	27 ± 9.8
Mass (kg)	77.9 ± 10.6
Height (cm)	178.6 ± 3.7
Body Surface Area (m^2)	1.93 ± 0.12
Body Fat (%)	13.3 ± 5.0
Peak oxygen consumption ($mL \cdot kg \cdot min^{-1}$)	47.6 ± 6.6
Absolute Peak Power Output (W)	283.0 ± 20.6
Relative Peak Power Output (W/kg)	3.7 ± 0.66

Table 1- Participant characteristics presented as mean ± SD.

Variable	TN	CS	HYPO-0.5°C	HYPO-1.0°C
Ratings of Perceived Exertion (6-20)*				
ISO0%	9.5 (8-11)[d]	10.5 (8.5-11)	12 (9.75-13)	12.5 (11-14.25)[a]
ISO100%	20 (18.5-20)	20 (17-20)	20 (19.25-20)	20 (19-20)
Thermal Comfort (1-4)*				
ISO0%	1 (1-1.25)[cd]	2 (2-3.25)[d]	4 (3-4)[a]	4 (4-4)[ab]
ISO100%	2 (1.75-3)	2 (2-3)	3.5 (2.75-4)	4 (2.75-4)
Thermal Sensation (1-7)*				
ISO0%	4 (3.75-4.5)[bcd]	2 (1-3)[a]	1 (1-1.25)[a]	1 (1-1)[a]
ISO100%	6 (4-6)[cd]	4.5 (3-6)[cd]	1 (1-2.25)[ab]	1 (1-2)[ab]
Shivering Scale (0-4)*				
Pre-TTE	0(0-0)[bcd]	0.5 (0-2)[acd]	3 (2.75-4)[ab]	3 (2.75-4)[ab]
Motivation (0-4)*				
Pre-TTE	3(2-4)	3.5 (2-4)	2.5 (1-3)	2 (0-4)

Table 2 – Perceptual responses collected during the TTE at ISO0% and ISO100% presented as median (Quartile 1 – Quartile 3) for the four experimental conditions (all n = 10 males). TN – Thermoneutral, CS = Cold Skin/Shell, HYPO-0.5°C = mild hypothermia of Δ-0.5°C from Baseline, HYPO-1.0°C = mild hypothermia of Δ-1.0°C from Baseline. * indicates a significant condition effect ($p < 0.05$) using a 2 X 2 repeated measures ANOVA or 1 X 4 repeated measures ANOVA for motivation. Post-hoc comparisons using Wilcoxon signed rank tests are ~~at can be~~ interpreted as: [a] significantly different ($p < 0.008$) from TN, [b] significantly different from CS, [c] significantly different from HYPO-0.5°C, [d] significantly different from HYPO-1.0°C.

Dose-Dependent Impact of Skin/ Core Cooling on Endurance Capacity

TN
22°C air
= Skin
= Core

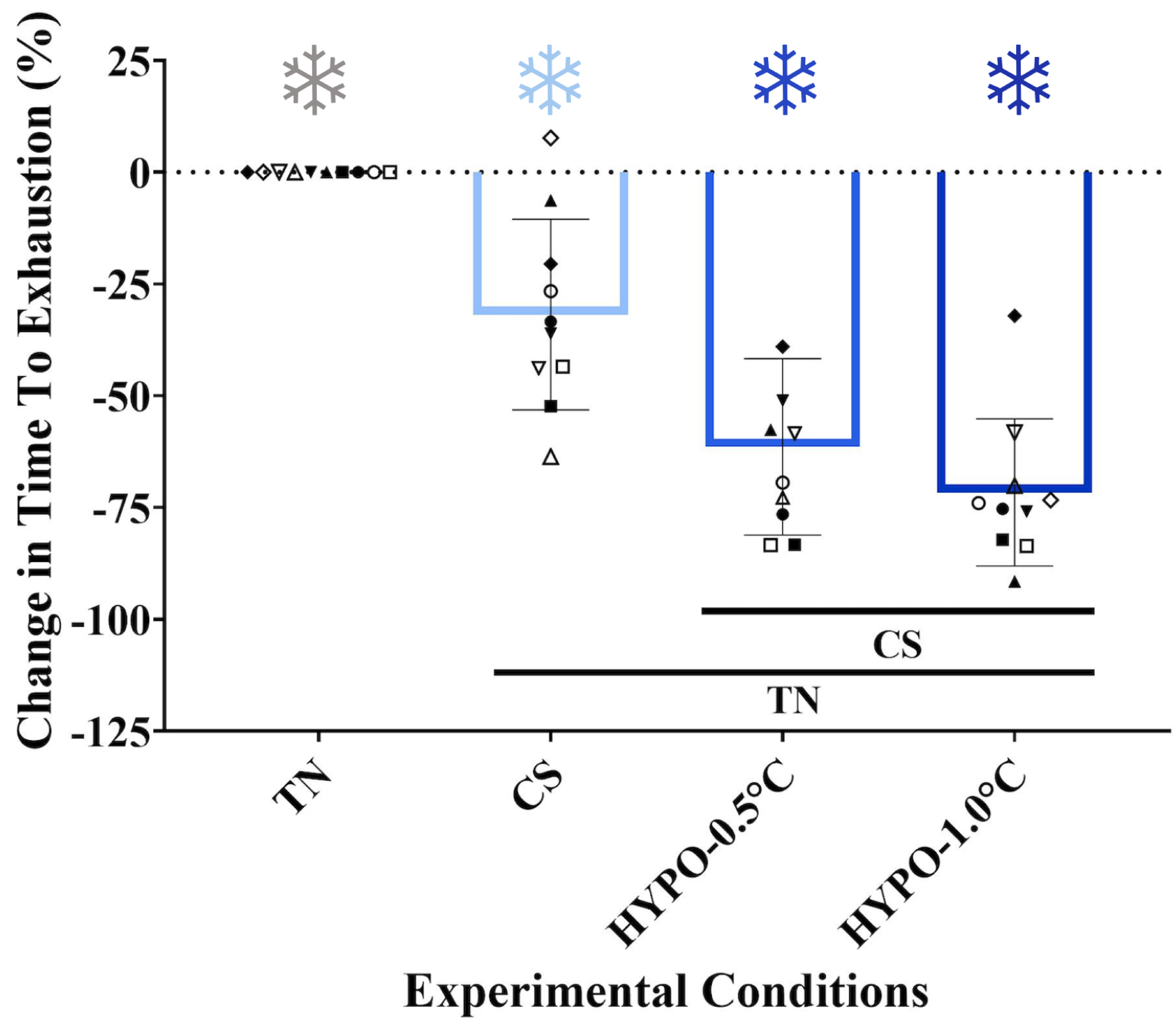
CS
0°C air
↓Skin
= Core

HYPO-0.5°C
0°C air
↓Skin
↓Core 0.5°C

HYPO-1.0°C
0°C air
↓Skin
↓Core 1.0°C

Time to exhaustion

70% peak power output



Skin cooling by itself impaired exercise capacity ~30%; core cooling impaired another ~30-40%