Full title:

The effect of acute heat exposure on the determination of exercise thresholds from ramp and step incremental exercise

Submission type:

Original Investigation

Subject Area:

Applied Sport Sciences – European Journal of Applied Physiology

Author details:

1. Gil Bourgois

Affiliations:

Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium

Univ. Lille, Univ. Artois, Univ. Littoral Côte d'Opale, ULR 7369 - URePSSS - Unité de Recherche Pluridisciplinaire Sport Santé Société, F-59000 Lille, France

ORCID: 0000-0001-8464-6017

2. Alessandro Colosio

Affiliations:

Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium

ORCID: 0000-0001-9091-2473

3. Kevin Caen

Affiliations:

Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium

Centre of Sports Medicine, Ghent University Hospital, Ghent, Belgium

ORCID: 0000-0002-2116-7438

4. Jan G. Bourgois

Affiliations:

Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium

Centre of Sports Medicine, Ghent University Hospital, Ghent, Belgium

ORCID: 0000-0001-8972-1573

5. Patrick Mucci

Affiliations:

Univ. Lille, Univ. Artois, Univ. Littoral Côte d'Opale, ULR 7369 - URePSSS - Unité de Recherche Pluridisciplinaire Sport Santé Société, F-59000 Lille, France
ORCID : 0000-0001-6703-1600

6. Jan Boone
Affiliations:
Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium
Centre of Sports Medicine, Ghent University Hospital, Ghent, Belgium
ORCID: 0000-0002-8485-6169

Corresponding author:
Jan Boone
Department of Movement and Sports Sciences, Ghent University
Postal Address: Watersportlaan 2, 9000 Ghent, Belgium
Tel.: +32 9 264 63 02
Email address: jan.boone@ugent.be

Running title: Effect of acute heat exposure on exercise thresholds

Abstract word count: 247
Text-only word count: 4469

Number of references: 44

Number of figures: 2
Number of tables: 1

Author contributions: GB, JGB, PM and JB conceived and designed research. GB, AC and KC conducted the experiments and analysed the data. GB, AC and JB wrote the manuscript. All authors revised and approved the manuscript.

Funding: This research was funded by the Special Research Fund of the Ghent University (Ghent, Belgium) in the context of a doctoral fellowship (n° BOF.DOC.2019.0033.01).

Conflicts of interest/Competing interests: No conflicts of interest, financial or otherwise, are declared by the authors

Ethics approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the ethical committee of the Ghent University Hospital (B6702020000260) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Acknowledgments: The authors would like to thank the subjects for their commitment to the study. This study was funded by the Special Research Fund of the Ghent University (Ghent, Belgium).

Consent to participate: Verbal and written informed consent was obtained from all individual participants included in the study.

Consent for publication: All participants provided verbal and written informed consent for publication of data presented within this research study as part of their informed consent form.

Availability of data and material: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

ABSTRACT

The aim of this study was to examine how respiratory (RT) and lactate thresholds (LT) are affected by acute heat exposure in the two most commonly used incremental exercise test protocols (RAMP and STEP) for functional evaluation of aerobic fitness, exercise prescription and monitoring training intensities. Eleven physically active male participants performed four incremental exercise tests, two RAMP (30 W·min^{-1}) and two STEP (40 W·3 min^{-1}), both in 18°C (TEMP) and 36°C (HOT) with 40 % relative humidity to determine 2 RT and 16 LT, respectively. Distinction was made within LT, taking into account the individual lactate kinetics (LT_{IND}) and fixed value lactate concentrations (LT_{FIX}). A decrease in mean power output (PO) was observed in HOT at LT (-6.2 ± 1.9 %), more specific LT_{IND} (-5.4 ± 1.4 %) and LT_{FIX} (-7.5 ± 2.4 %), compared to TEMP, however not at RT (-1.0 ± 2.7 %). The individual PO difference in HOT compared to TEMP over all threshold methods ranged from -53 W to +26 W. Mean heart rate (HR) did not differ in LT, while it was increased at RT in HOT (+10 ± 8 bpm). This study showed that exercise thresholds were affected when ambient air temperature was increased. However, a considerable degree of variability in the sensitivity of the different threshold concepts to acute heat exposure was found and a large individual variation was noticed. Test design and procedures should be taken into account when interpreting exercise test outcomes.

KEY WORDS

Heat; incremental exercise test; respiratory threshold; lactate threshold

INTRODUCTION

Incremental exercise tests are widely used to determine exercise thresholds that demarcate the intensity domains of moderate, heavy and severe exercise (Gaesser & Poole, 1996). By use of these thresholds, aerobic fitness can be assessed and exercise prescription can be optimized according to the specific profile of the sports discipline and athlete (Bourgois et al., 2019). It has been shown that incremental exercise tests with continuous linear (RAMP) or stepwise (STEP) increases in intensity can provide valuable insights into these thresholds, although they do not represent the gold standard procedures (i.e., multiple constant load exercise tests) (Keir et al., 2015). Despite a high feasibility (i.e., time-efficiency) of these protocols, appropriate protocol design and careful data analysis by experienced physiologists or coaches are required for accurate determination and interpretation of exercise thresholds (Jamnick et al., 2018; Caen et al., 2021). RAMP tests typically last between 8 and 12 min and are mostly used when thresholds are determined from pulmonary gas exchange variables (Keir et al., 2022), with maximal oxygen uptake ($\dot{V}O_2max$) and respiratory thresholds (RT), i.e., gas exchange threshold (GET) and respiratory compensation point (RCP), as key outcomes. STEP tests are more common when blood lactate measurement is the main parameter for threshold determination, and a minimum stage length (i.e., 3 min) is proposed (Bentley, 2007). Over the years, a large variety of lactate thresholds (LT) methods has been suggested and utilized (Faude et al., 2009; Jamnick et al., 2018). Some of these methods take into account the individual kinetics of the lactate-performance curve (LT_{IND}; e.g., D_{max} method; Cheng et al., 1992), while others rely on fixed blood lactate concentrations (LT_{FIX}; e.g., 4 mmol·L^{-1}; Kindermann et al., 1979).

Furthermore, even when the testing procedure and analysis are applied adequately, the occurrence of these exercise thresholds can be influenced by multiple factors, including environmental conditions. In fact, heat can alter the physiological responses to exercise (Périard et al., 2021). A redistribution of blood to the skin for heat dissipation leads to a higher cardiovascular strain (Rowell, 1974). Furthermore, there is a shift toward a greater reliance on the glycolytic metabolism (Febbraio et al., 1994), resulting in a decreased mechanical efficiency (Hettinga et al., 2007). Subsequently, the impact of heat on parameters used for exercise prescription and monitoring training intensity, i.e., power output (PO), heart rate (HR), blood lactate concentration ($[BLa^-]$) and oxygen uptake ($\dot{V}O_2$), can result in a modified occurrence of LT from STEP and/or RT from RAMP during incremental exercise.

Several studies reported changes in threshold occurrence when exercise testing is executed in hot environmental conditions (Tyka et al., 2009; 2010; de Barros et al., 2011; Lorenzo et al., 2011; Maunder et al., 2021) and made suggestions on how this additional information could be used for training prescription and monitoring during training camps and tournaments in hot environments. However, these studies do not compare different incremental exercise tests (RAMP and STEP) and/or only include limited exercise threshold concepts.

Therefore, the purpose of this study is to examine how different exercise thresholds (RT and LT) are affected by acute heat exposure in the two most commonly used incremental exercise test protocols (RAMP and STEP) for functional evaluation of aerobic fitness. This will allow us to gain more insight into the physiological mechanism of exercise threshold determination and provide practical implications for sports scientists and coaches. We hypothesize that short-term heat exposure (i.e., duration of the test) will have an impact on PO and HR at all exercise thresholds, although we expect differences related to the protocol of the test (i.e., time duration-intensity relationship of RAMP vs. STEP) and the methodology of LT determination (i.e., lactate kinetics in LT_{IND} vs. LT_{FIX}). Furthermore, we hypothesize that thresholds taking place at a higher intensity will be affected more as heat exposure time is increased, accelerating cardiorespiratory and metabolic perturbations.

METHODS

Participants

Eleven male participants (age: 24.9 ± 1.7 years, height: 1.82 ± 0.06 m, body mass: 77.0 ± 6.6 kg) volunteered in this study. All participants were physically active, and performed recreational physical exercise on a self-reported basis of 5.0 ± 1.4 hours per week. Participants did not train in hot environments 3 months preceding the study to avoid heat acclimation/acclimatization effects. Participants completed a medical questionnaire and underwent a medical examination. Participants did not report any history of cardiovascular, respiratory or metabolic disease. After receiving a description of the procedure of the experiment, all participants gave their written informed consent. The protocol was in accordance with the Declaration of Helsinki and was approved by the ethical committee of the Ghent University Hospital (Ghent, Belgium).

Study design

General procedure. All participants performed four incremental exercise tests on an electromagnetically braked cycle ergometer (Cyclus 2, RBM Elektronik-Automation, Leipzig, Germany) at the Sport Science Laboratory Jacques Rogge of the Ghent University (Ghent, Belgium, sea level) between 1.00 p.m. and 6.00 p.m. to limit variability due to the circadian rhythm. Each participant performed all tests at the same time of the day (± 30 min) with a minimum of 72 hours between two tests. Trials were completed during the spring months. Two ramp and two step incremental exercise tests were executed, one of each in temperate (TEMP: 18 ± 1°C) and one of each in hot environmental conditions (HOT: 36 ± 1°C), with partial counterbalancing to deal with practice effects. Air relative humidity (RH) was kept constant at 40 ± 3 %. All exercise tests took place in a built-in climatic chamber. Before the start of each exercise test, participants were seated for 10 min to accommodate to the environmental conditions. Participants were asked to maintain the same type of meals at the day of an exercise test and to drink 500 mL of water over 2 hours prior to the beginning of the test. Participants were instructed to abstain from any exhaustive exercise 24 hours leading up to an exercise test and to refrain from consumption of caffeine and alcohol for 24 hours prior to testing. During the first test, participants were instructed to choose their cadence between 70 and 90 revolutions per minute (rpm), and maintain their preferred cadence during all upcoming exercise tests. Strong verbal encouragement was provided throughout all exercise tests to ensure maximum effort. The protocol was terminated at volitional exhaustion, which was defined as the inability to maintain a minimal cadence of 70 rpm for more than 5 consecutive seconds. HR was monitored on a continuous basis (H7 Sensor; Polar, Kempele, Finland).

RAMP test. Warm-up consisted of 6 min cycling at 120 W, 2 min seated rest and 4 min baseline cycling at 70 W. Subsequently, the work rate increased continuously and linear with 30 $W \cdot min^{-1}$, as this would result in a test duration of 8-12 min in our population based on anthropometrics and reported physical exercise. Pulmonary gas exchanges for the determination of $\dot{V}O_{2peak}$, GET and RCP were measured on a breath-by-breath basis using a metabolic instrument (Cortex MetaLyzer 3B; Cortex Biophysik, Leipzig, Germany).

STEP test. The test started at a work rate of 80 W for 3 min and increased stepwise with 40 W every 3 min to obtain at least five $[BLa^-]$ measurements. At the end of each stage, 20 µL of blood from the right middle finger was collected into a capillary tube and analysed for $[BLa^-]$ (Biosen C-Line; EKF-diagnostic GmbH, Magdeburg, Germany). Peak $[BLa^-]$ ($[BLa^-]_{peak}$) was obtained 1 min after cessation of the exercise test.

Data analysis

For all exercise thresholds, corresponding values of PO and HR were determined and the differences in PO and HR between TEMP and HOT were calculated and expressed as the relative change (%) compared to values of TEMP (Δ). PO at thresholds in TEMP were calculated relative to peak PO ($\%PO_{peak}$) within the respective test protocol, to express the relationship between PO-Δ and (relative) exercise intensity.

RAMP test. Breath-by-breath data were averaged into 10 s intervals. $\dot{V}O_{2peak}$ was determined as the average of the highest three consecutive 10 s values. Two respiratory thresholds were determined by four independent researchers using four different criteria for each threshold. The mean of the closest three values was used. GET was defined as [1] the point where $\dot{V}CO_2$ increased disproportionately to $\dot{V}O_2$ using the V-slope method, [2] the first departure from the linear increase in ventilation ($\dot{V}_E$), [3] an increase in $\dot{V}_E/\dot{V}O_2$ without a simultaneous increase in $\dot{V}_E/\dot{V}CO_2$ and [4] the first rise in end-tidal oxygen tension ($P_{ET}O_2$) (Beaver et al., 1986; Binder et al., 2008). RCP corresponded to [1] the point where $\dot{V}_E$ increased disproportionately to $\dot{V}CO_2$, [2] the second departure from linearity in $\dot{V}_E$, [3] an increase in both $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$ and [4] the deflection point of end-tidal carbon dioxide tension ($P_{ET}CO_2$) (Wasserman, 1984; Binder et al., 2008). To obtain the precise work rate at which GET occurred, an individual correction was made, i.e., to account for the mean response time (MRT) of the $\dot{V}O_2$ kinetics. MRT was quantified as the time interval between the onset of the ramp and the intersection of the forward extrapolation of the baseline $\dot{V}O_2$ and the backwards extrapolation of the linear $\dot{V}O_2$/time relationship below the GET (Boone & Bourgois, 2012). For RCP, an additional correction was made to close the gap for the extra dissociation of the $\dot{V}O_2$/PO relationship between ramp incremental exercise and constant work rate exercise at higher intensities (Caen et al., 2020). Oxygen pulse (O_2 pulse: $\dot{V}O_2$/HR) was calculated as an indirect indicator of cardiac stroke volume (SV) at peak level and the two RT.

STEP test. Sixteen thresholds were calculated based on [BLa^-], using nine threshold methods. A distinction was made between individual (LT_{IND}) and fixed value (LT_{FIX}) lactate thresholds.

Individual lactate thresholds:

1. Log-log: The lactate curve was divided into two segments and the intersection point of the two lines with the lowest residuals sum of squares was taken as the lactate threshold (Beaver et al., 1985).
2. Baseline + absolute value(s) (Bsln + $mmol \cdot L^{-1}$): The intensity at which [BLa^-] increased 0.5 (Bsln + 0.5), 1.0 (Bsln + 1.0) or 1.5 (Bsln + 1.5) $mmol \cdot L^{-1}$ above baseline value (Berg et al., 1990; Zoladz et al., 1995).
3. D_{max}: The point on the third-order polynomial regression curve that yielded the maximum perpendicular distance to the straight line formed by the two end points of the curve (Cheng et al., 1992).
4. Modified D_{max} ($ModD_{max}$): The intensity at the point on the third order polynomial regression curve that yielded the maximal perpendicular distance to the straight line formed by the point preceding the first rise in [BLa^-] of > 0.4 $mmol \cdot L^{-1}$ lactate and the final lactate point (Bishop et al., 1998).
5. Exponential D_{max} ($Exp\text{-}D_{max}$): The point on the exponential regression curve that yielded the maximum perpendicular distance to the straight line formed by the two end points of the curve (Hughson et al., 1987; Machado et al., 2012).

6. Log-log modified D_{max} (Log-Poly-ModD_{max}): The intensity at the point on the third order polynomial regression curve that yielded the maximal perpendicular distance to the straight line formed by the intensity associated with the log-log LT and the final lactate point (Jamnick et al., 2018).

7. Log-log exponential modified D_{max} method (Log-Exp-ModD_{max}): The intensity at the point on the exponential plus-constant regression curve that yielded the maximal perpendicular distance to the straight line formed by the intensity associated with the log-log LT and the final lactate point (Jamnick et al., 2018).

8. First and second lactate turning points: The lactate curvature is divided into three segments. Two double-linear fits are performed, which the intersection points between the lines (segments) are considered as Lactate Threshold 1 (LT_1) and Lactate Threshold 2 (LT_2) (Binder et al., 2008).

Fixed value lactate thresholds:

9. Fixed lactate thresholds or onset of blood lactate accumulation (OBLA) values of 2.0 (OBLA 2.0), 2.5 (OBLA 2.5), 3.0 (OBLA 3.0), 3.5 (OBLA 3.5), or 4.0 (OBLA 4.0) $mmol \cdot L^{-1}$ (Kindermann et al., 1979; Skinner & McLellan, 1980; Heck et al., 1985).

Statistical analysis

All data were expressed as mean values and standard deviations (SD) for n = 11. A priori sample size calculations have been performed in G*Power 3.1.9 (University Düsseldorf, Germany) with significance level 0.05 and power 80 %. An estimated effect size of 0.65 results in a total sample size of n=11. Participants served as their own controls. SPSS statistics 25 (IBM Corp., Armonk, NY) was used for statistical analysis. The Shapiro-Wilk test was used to confirm normal distribution of the data. Repeated-Measures (RM) ANOVA (2 × 2) was performed to investigate differences in time to exhaustion (TTE) and peak performance parameters (PO and HR) between TEMP and HOT in RAMP and STEP. Paired-samples t tests were used to compare $\dot{V}O_2$ in RAMP and $[BLa^-]$ in STEP between TEMP and HOT.

RM ANOVA was used to observe a difference how thresholds determined in RAMP (i.e., RT) and STEP (i.e., LT) are affected by heat (design: 18 thresholds × 2 conditions), and this was done for PO and HR corresponding to the threshold. If a significant effect was seen, post hoc paired samples t tests with Bonferroni correction were executed for comparison between TEMP and HOT for one threshold at a time.

Significance was set at $p < 0.05$ and 95 % Confidence Interval ($CI_{95\%}$) was given. Cohen's d effect size (ES) was calculated to standardize mean differences. Pearson correlation coefficient (*r*) was used to mark a linear relationship between absolute and relative exercise intensity (i.e., PO and $\%PO_{peak}$) in TEMP and the size of difference in PO (Δ) between TEMP and HOT.

RESULTS

At peak level, no interaction effect ($F = 2.078$; $p = 0.180$) was found for PO_{peak} in TEMP and HOT for RAMP (361 ± 29 W vs. 353 ± 40 W) and STEP (306 ± 31 W vs. 288 ± 29 W); nonetheless, there was a main effect of temperature ($F = 24.605$; $p < 0.001$), indicating that the PO_{peak} in HOT was lower compared to TEMP. On the other hand, significant interaction effects were found for TTE ($F = 9.718$; $p = 0.011$) and HR ($F = 7.111$; $p = 0.024$). TTE was reduced in STEP (1018 ± 140 s vs. 937 ± 130 s; $p < 0.001$) in HOT compared to TEMP, but not in RAMP (581 ± 59 s vs. 566 ± 80 s; $p = 0.212$) and HR was higher in RAMP (182 ± 10 bpm vs. 187 ± 9 bpm; $p = 0.017$) in HOT compared to TEMP, but not in STEP (187 ± 8 bpm vs. 185 ± 7 bpm; $p = 0.346$). $[BLa^-]_{peak}$ did not differ in STEP between TEMP and HOT (12.14 ± 1.65 $mmol \cdot L^{-1}$ vs. 11.48 ± 2.17 $mmol \cdot L^{-1}$; $p = 0.198$). Furthermore, $\dot{V}O_{2peak}$ was higher in HOT in RAMP (3.93 ± 0.46 $L.min^{-1}$ vs. 4.19 ± 0.40 $L.min^{-1}$; $p < 0.001$) and O_2 pulse at peak level did not differ in RAMP (21.7 ± 3.0 $ml.bpm^{-1}$ vs. 22.5 ± 2.4 $ml.bpm^{-1}$; $p = 0.053$).

Table 1 gives an overview of all threshold methods (expressed as PO and HR) in TEMP and HOT within their respective exercise test protocol. When expressed as PO, a significant interaction effect ($F = 2.038$; $p = 0.012$) was seen for the effect of heat on thresholds, determined in RAMP and STEP, meaning that there is a difference in the way thresholds are impacted by heat exposure. Post hoc analysis shows a significant decrease in PO in HOT for all thresholds, except GET, RCP and the log-log method. When expressed as HR, a significant interaction effect ($F = 4.040$; $p < 0.001$) was found for the effect of heat on thresholds, determined in RAMP and STEP. Post hoc analysis shows a significant increase in HR in HOT at RT, but not LT. Figure 1 provides the representation of individual PO difference in HOT compared to TEMP for all threshold methods, with a range from -53 W to +26 W. $\dot{V}O_2$ was higher at GET (2.76 ± 0.30 $L.min^{-1}$ vs. 2.95 ± 0.32 $L.min^{-1}$; $p = 0.006$) and RCP (3.50 ± 0.44 $L.min^{-1}$ vs. 3.74 ± 0.40 $L.min^{-1}$; $p = 0.013$) in HOT.

A negative correlation was observed between the exercise intensity at which the thresholds occurred and the change in PO between TEMP and HOT, both for absolute PO (Fig. 2A; $r = -0.34$; $p < 0.001$) as relative to PO_{peak} (Fig. 2B; $r = -0.31$; $p < 0.001$).

DISCUSSION

In this study, we made a comparison between 18 exercise thresholds determined from two commonly used incremental test protocols (i.e., RAMP and STEP) in temperate (TEMP: 18°C) and hot (HOT: 36°C) environments with the same relative humidity (RH: 40 %). To our knowledge, this study is the first to comprehensively examine the effect of acute heat exposure on RT and LT in non-acclimatized physically active individuals.

Our first hypothesis was that short-term heat exposure (i.e., only the time duration of an incremental exercise test) would have a negative impact on all exercise thresholds. We found a significant interaction effect of ambient air temperature on the occurrence of the thresholds for PO, meaning that not all thresholds were impacted in the same way. This points at a considerable degree of variability in the sensitivity of the different threshold concepts to acute heat exposure. The PO at some thresholds was highly impacted (e.g., OBLA 2.0) as shown in the medium to large effect sizes (0.50-0.81), whereas in others, PO remained unchanged (e.g., GET). The mean decrease of PO at the different thresholds in our study was less pronounced (RT: -1.0 ± 2.7 % and LT: -6.2 ± 1.9 %), as compared to other studies investigating performance decrements in heat. Maunder et al. (2021) reported decreases for OBLA 2.0, OBLA 3.0 and OBLA 4.0, respectively, of 16 %, 13 % and 10 % between 18 and 36°C (60 % RH) in 16 competitive endurance-trained males, and a 17 % and 12 % decrease is noticed, respectively, at first (i.e., GET) and second (i.e., RCP) RT. de Barros et al. (2011) found that PO corresponding to RCP decreased by 18 % in 40°C in comparison to 22°C (50 % RH) for eight healthy young untrained male participants. Furthermore, Tyka et al. (2009; 2010) reported a 13 % and 11 % decrease at, respectively, LT (Exp-D_{max}) and GET (V-slope method) in 37°C compared to 23°C (55 % RH). Lorenzo et al. (2011) found an overall decrease of 12 % in power output at several blood- and ventilation-based thresholds in 12 highly trained endurance cyclists (10 men and 2 women) when cycling in 38°C compared to 13°C (30 % RH).

The above variation in results coming from different studies can be explained by differences in test designs and procedures. First, exercise tests took place in various environmental conditions (i.e., ambient air temperature and RH) using different test populations, so that a direct comparison is difficult. Second, in the present study, participants were exposed to hot environmental conditions for ~30 min (i.e., 10 min rest + exercise test). This exposure time is shorter than in the study of Maunder et al. (2021) and Tyka et al. (2010), where participants rested passively for 20 min and 30 min, respectively. Other studies reported the use of immersion in a hot bath (41°C) for 30 min to induce whole-body hyperthermia before start of incremental exercise (Lorenzo et al., 2011) or do not report the time of exposure before start of the test (de Barros et al., 2011). Furthermore, we speculate that the impact of heat exposure on exercise thresholds, using a protocol that prolongs the duration of the incremental exercise test (e.g., RAMP with a smaller ramp slope or STEP with longer stages), would be more fierce. This could also be the reason why our hypothesis, that thresholds taking place at a higher intensity will be affected more as heat exposure time is increased, was only partially supported by a weak correlation (see Fig. 2). The total duration of our protocol was too short to induce severe cardiorespiratory and metabolic perturbations, even in the thresholds occurring at higher intensities. Finally, it should be pointed out that the exercise test protocol is different. A single RAMP protocol with continuous increase in PO is preferred to determine RT as it is the most appropriate way to detect break point in the slope of the gas exchange and ventilatory response patterns (Keir et al., 2022). This is in contrast to other studies, where they used various STEP protocols to determine RT (Tyka et al., 2009; Tyka et al., 2010; de Barros et al., 2011) or merged STEP and RAMP into one exercise test protocol (Maunder et al., 2021), which will affect threshold determination.

The determination of LT in STEP is based on different underlying methodologies, i.e., LT_{IND} or LT_{FIX}. We observed an alteration in lactate kinetics in HOT (LT_{IND}:-5.4 ± 1.4 % and LT_{FIX}: -7.5 ± 2.4 %), meaning that all LT methods (except log-log method) are sensitive to heat exposure. Higher [BLa^-] values were observed at the same absolute intensities in HOT compared to TEMP, resulting in lower PO at OBLA 2.0 – 4.0. This could indicate that there is a more pronounced production rate of La^- due to a greater reliance on the glycolytic metabolism, possible mediated by a higher thermal strain (i.e., elevated muscle temperature) and an increased sympathoadrenal response (i.e., increased circulating epinephrine) for the same absolute PO (Febbraio et al., 1994, 1996). Although, it should be emphasized that BLa^- accumulation is the result of a balance between production by the muscles and clearance from the blood by active and inactive muscle mass, heart, brain, liver and kidneys. A redistribution of the blood flow toward the skin (i.e., vasodilatation for heat dissipation) occurs with heat exposure, suggesting a lower La^- elimination rate (Brooks, 2018; Rowell et al., 1968). The determination of LT by means of the D_{max} method (D_{max}, ModD_{max}, Exp-D_{max}, Log-Poly-ModD_{max}, Log-Exp-ModD_{max}) depends on baseline [BLa^-], lactate kinetics and $[BLa^-]_{peak}$. An equal mean $[BLa^-]_{peak}$ was obtained at PO_{peak} (12.14 ± 1.65 mmol·L^{-1} vs. 11.48 ± 2.17 mmol·L^{-1}), although PO_{peak} was lower in HOT (306 ± 31 W vs. 288 ± 29 W). As a consequence, the course of the [BLa^-]-PO curve shifted to the left thus also resulting in a lower PO for the LT_{FIX} thresholds.

We found a higher HR for a given submaximal absolute PO, which can be attributed to the direct temperature effect on intrinsic HR at the sinoatrial node (Jose et al., 1970) and/or indirect effect by a reduced venous return due to increased skin blood flow (Rowell, 1974). In the context of exercise prescription, Maunder et al. (2021) proposed to rely on the HR instead of PO in the early phase of a heat acclimation/acclimatization camp, as HR at the thresholds did not differ between TEMP and HOT. This is in line with what we found in our study in STEP (i.e., equal HR and reduced PO). However, it must be pointed out that they do not take into account the negative heat effects during prolonged exercise at submaximal intensity. Deterioration of cardiac function and more specific reduction cardiac output will be more pronounced with prolonged (intense) exercise in heat as core temperature increases. When prescribing exercise based on HR, it is important that this is in accordance with the correct metabolic intensity (Teso et al., 2022), however, this is complicated in heat as both absolute and relative intensity will change over time.

We found that RT, with PO adjustment for GET (Boone & Bourgois, 2012) and RCP (Caen et al., 2020), in RAMP were less susceptible to heat. This might be due to a difference in duration-intensity ratio between RAMP and STEP where time spent above 50 %PO_{peak} was almost double in STEP compared to RAMP (669 ± 67 s vs. 357 ± 34 s). As such, the heat strain, which is a function of absolute intensity and time, could be less pronounced in RAMP vs. STEP. We found that GET and RCP were identified at a higher $\dot{V}O_2$, and thus a higher metabolic intensity or internal load. However, converted to PO or external load, the RT did not change. It has been suggested that extra myocardial $\dot{V}O_2$ in HOT is the reason, at least to a certain degree, for the higher

$\dot{V}O_2$ at a given submaximal power output. Gross efficiency during cycling is impacted by sustaining muscle blood flow in combination with a higher skin blood flow for heat dissipation (Hettinga et al., 2007; Nielsen et al., 1990). The relative intensity (i.e., %$\dot{V}O_{2peak}$), however, did not change at GET (70 ± 3 %) and RCP (89 ± 4 %) between TEMP and HOT, as also $\dot{V}O_{2peak}$ reached during RAMP in HOT was higher compared to TEMP. This might be surprising as several other studies (Arngrímsson et al., 2004; James et al., 2017; Lorenzo et al., 2011) found that $\dot{V}O_{2peak}$ is impaired in the heat, attributed to a lower cardiac output (González-Alonso & Calbet, 2003) and increases in core temperature limiting $\dot{V}O_{2peak}$ (Arngrimsson et al., 2004). Others, however, observed no reduction in $\dot{V}O_{2peak}$ (Rowell et al., 1965; Schlader et al., 2011; Tyka et al., 2010) or even an increase (Kuo et al., 2021; Lafrenz et al., 2008), possibly related to the short duration of the test (Rowell, 1974). The characteristics of the participants, who are physically active but not habituated to cycling exercise, must also been taken into account. In this context, it is possible that in TEMP, the exercise tests were terminated as a consequence of fatigue in the locomotor muscles instead of cardiopulmonary exhaustion. In our study, we observed, not only submaximal, but also at peak level a higher HR, so that the O_2 pulse (oxygen consumption per heart beat) is equal at GET, RCP and peak in both environmental conditions. Clearly, further investigation on the effects of acute heat exposure on limitations of exercise performance is required.

In conclusion, acute short-term heat exposure, by means of increased ambient air temperature, does impact RT and LT expressed in PO or HR, determined from a ramp (30 $W \cdot min^{-1}$) or step (40 $W \cdot 3\ min^{-1}$) incremental exercise test. Results regarding the outcomes of exercise tests in heat are still diverse and cannot be generalized without taking into account the underlying components, as consistency in methodology of exercise testing, threshold determination and specific environmental conditions are key. Based on PO and/or physiological values (HR, BLa^- and $\dot{V}O_2$) obtained from one exercise test in heat, translation to practice remains complicated. However, given the large variation in response to heat exposure (see Fig.1), even a short incremental exercise test with acute heat exposure can give valuable insight on the acute heat response of an athlete. Yet, performing exercise tests in a broad range of environmental conditions provide the opportunity to gather useful information for sports scientists and coaches to optimize exercise prescription and monitoring exercise intensity in moderate physically active individuals. Therefore, every case has to be (re)viewed individually by an experienced staff, so that optimal training outcomes can be achieved.

378 REFERENCES

1. Arngrimsson, S. A., Petitt, D., Borrani, F., Skinner, K., & Cureton, K. (2004). Hyperthermia and maximal oxygen uptake in men and women. *European Journal of Applied Physiology*, *92*(4–5), 524–532. https://doi.org/10.1007/s00421-004-1053-1
2. Beaver, W. L., Wasserman, K., & Whipp, B. (1985). Improved detection of lactate threshold during exercise using a log-log transformation. *J Appl Physiol*, *59*(6), 1936–1940. https://doi.org/10.1152/jappl.1985.59.6.1936
3. Beaver, W. L., Wasserman, K., & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol*, *60*(6), 2020–2027. https://doi.org/10.1152/jappl.1986.60.6.2020
4. Berg, A., Jakob, E., Lehmann, M., Dickhuth, H., Huber, G., & Keul, J. (1990). Current aspects of modern ergometry. *Pneumologie (Stuttgart, Germany)*, *44*(1), 2–13.
5. Binder, R., Wonisch, M., Corra, U., Cohen-Solal, A., Vanhees, L., Saner, H., & Schmid, J. P. (2008). Methodological approach to the first and second lactate threshold in incremental cardiopulmonary exercise testing. *European Journal of Cardiovascular Prevention & Rehabilitation*, *15*(6), 726–734. https://doi.org/10.1097/HJR.0b013e328304fed4
6. Bishop, D., Jenkins, D. G., & Mackinnon, L. T. (1998). The relationship between plasma lactate parameters, Wpeak and 1-h cycling performance in women. *Med Sci Sports Exerc*, *30*(8), 1270–1275. https://doi.org/10.1097/00005768-199808000-00014
7. Boone, J., & Bourgois, J. (2012). The Oxygen Uptake Response to Incremental Ramp Exercise Methodogical and Physiological Issues. *Sports Med*, *42*(6), 511–526.
8. Bourgois, J. G., Bourgois, G., & Boone, J. (2019). Perspectives and Determinants for Training-Intensity Distribution in Elite Endurance Athletes. *International Journal of Sports Physiology and Performance*, *14*(8), 1151–1156. https://doi.org/10.1123/ijspp.2018-0722
9. Brooks, G. A. (2018). The Science and Translation of Lactate Shuttle Theory. *Cell Metabolism*, *27*(4), 757–785. https://doi.org/10.1016/j.cmet.2018.03.008
10. Caen, K., Boone, J., Bourgois, J. G., Colosio, A. L., & Pogliaghi, S. (2020). Translating Ramp VO2 into constant power output: a novel strategy that minds the gap. *Med Sci Sports Exerc*, *52*(9), 2020–2028. https://doi.org/10.1249/MSS.0000000000002328
11. Caen, K., Pogliaghi, S., Lievens, M., Vermeire, K., Bourgois, J. G., & Boone, J. (2021). Ramp vs. step tests: valid alternatives to determine the maximal lactate steady-state intensity? *European Journal of Applied Physiology*, *121*(7), 1899–1907. https://doi.org/10.1007/s00421-021-04620-9
12. Cheng, B., Kuipers, H., Snyder, A. C., Keizer, H. A., Jeukendrup, A., & Hesselink, M. (1992). A new approach for the determination of ventilatory and lactate thresholds. *International Journal of Sports Medicine*, *13*(7), 518–522. https://doi.org/10.1055/s-2007-1021309

13. de Barros, C. L. M., Mendes, T. T., Mortimer, L. Á. C. F., Simões, H. G., Prado, L. S., Wisloff, U., & Silami-Garcia, E. (2011). Maximal Lactate Steady State is Altered in the Heat. *International Journal of Sports Medicine*, *32*(10), 749–753. https://doi.org/10.1055/s-0031-1277191
14. Faude, O., Kindermann, W., & Meyer, T. (2009). Lactate threshold concepts: How valid are they? *Sports Medicine*, *39*(6), 469–490. https://doi.org/10.2165/00007256-200939060-00003
15. Febbraio, M. A., Carey, M. F., Snow, R. J., Stathis, C. G., & Hargreaves, M. (1996). Influence of elevated muscle temperature on metabolism during intense, dynamic exercise. *American Journal of Physiology - Regulatory Integrative and Comparative Physiology*, *271*(5), R1251–R1255. https://doi.org/10.1152/ajpregu.1996.271.5.r1251
16. Febbraio, M. A., Snow, R. J., Stathis, C. G., Hargreaves, M., & Carey, M. F. (1994). Effect of heat stress on muscle energy metabolism during exercise. *J. Appl. Physiol*, *77*(6), 2827–2831. https://doi.org/10.1152/jappl.1994.77.6.2827
17. Gaesser, G. A., & Poole, D. C. (1996). The slow component of oxygen uptake kinetics in humans. *Exercise & Sport Science Reviews*, *24*(1), 35–70.
18. González-Alonso, J., & Calbet, J. A. L. (2003). Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation*, *107*(6), 824–830. https://doi.org/10.1161/01.CIR.0000049746.29175.3F
19. Heck, H., Mader, A., Hess, G., Mücke, S., Muller, R., & Hollmann, W. (1985). Justification of the 4-mmol/l lactate threshold. *Int J Sports Med*, *6*(3), 117–130. https://doi.org/10.1055/s-2008-1025824
20. Hettinga, F. J., De Koning, J. J., de Vrijer, A., Wüst, R. C. I., Daanen, H. A. M., & Foster, C. (2007). The effect of ambient temperature on gross-efficiency in cycling. *European Journal of Applied Physiology*, *101*(4), 465–471. https://doi.org/10.1007/s00421-007-0519-3
21. Hughson, R. L., Weisiger, K. H., & Swanson, G. D. (1987). Blood lactate concentration increases as a continuous function in progressive exercise. *Journal of Applied Physiology*, *62*(5), 1975–1981. https://doi.org/10.1152/jappl.1987.62.5.1975
22. James, C. A., Hayes, M., Willmott, A. G. B., Gibson, O. R., Flouris, A. D., Schlader, Z. J., & Maxwell, N. S. (2017). Defining the determinants of endurance running performance in the heat. *Temperature*, *4*(3), 314–329. https://doi.org/10.1080/23328940.2017.1333189
23. Jamnick, N. A., Botella, J., Pyne, D. B., & Bishop, D. J. (2018). Manipulating graded exercise test variables affects the validity of the lactate threshold and VO2peak. *PLoS ONE*, *13*(7), e0199794. https://doi.org/10.1371/journal.pone.0199794
24. Jose, A. D., Stitt, F., & Collison, D. (1970). The effects of exercise and changes in body temperature on the intrinsic heart rate in man. *American Heart Journal*, *79*(4), 488–498. https://doi.org/10.1016/0002-8703(70)90254-1
25. Keir, D. A., Fontana, F. Y., Robertson, T. C., Murias, J. M., Paterson, D. H., Kowalchuk, J. M., & Pogliaghi,

S. (2015). Exercise Intensity Thresholds: Identifying the Boundaries of Sustainable Performance. *Medicine and Science in Sports and Exercise*, *47*(9), 1932–1940. https://doi.org/10.1249/MSS.0000000000000613

26. Keir, D. A., Iannetta, D., Mattioni Maturana, F., Kowalchuk, J. M., & Murias, J. M. (2022). Identification of Non-Invasive Exercise Thresholds: Methods, Strategies, and an Online App. *Sports Medicine*, *52*(2), 237–255. https://doi.org/10.1007/s40279-021-01581-z
27. Kindermann, W., Simon, G., & Keul, J. (1979). The signifcance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training. *European Journal of Applied Physiology and Occupational Physiology*, *42*(1), 25–34. https://doi.org/10.1007/BF00421101
28. Kuo, Y., Cheng, C., & Kuo, Y. (2021). Determining Validity of Critical Power Estimated Using a Three-Minute All-Out Test in Hot Environments. *International Journal of Environmental Research and Public Health*, *18*(17), 9193. https://doi.org/10.3390/ijerph18179193
29. Lafrenz, A. J., Wingo, J. E., Ganio, M. S., & Cureton, K. J. (2008). Effect of Ambient Temperature on Cardiovascular Drift and Maximal Oxygen Uptake. *Med Sci Sports Exerc*, *40*(6), 1065–1071. https://doi.org/10.1249/MSS.0b013e3181666ed7
30. Lorenzo, S., Minson, C. T., Babb, T. G., & Halliwill, J. R. (2011). Lactate threshold predicting time-trial performance: impact of heat and acclimation. *J. Appl. Physiol*, *111*(1), 221–227. https://doi.org/10.1152/japplphysiol.00334.2011
31. Machado, F. A., Nakamura, F. Y., & de Moraes, S. M. F. (2012). Influence of regression model and incremental test protocol on the relationship between lactate threshold using the maximal-deviation method and performance in female runners. *Journal of Sports Sciences*, *30*(12), 1267–1274. https://doi.org/10.1080/02640414.2012.702424
32. Maunder, E., Plews, D. J., Merien, F., & Kilding, A. E. (2021). Stability of heart rate at physiological thresholds between temperate and heat stress environments in endurance-trained males. *International Journal of Sports Physiology and Performance*, *16*(8), 1204–1207. https://doi.org/10.1123/IJSPP.2020-0351
33. Nielsen, B., Savard, G., Richter, E. A., Hargreaves, M., & Saltin, B. (1990). Muscle blood flow and muscle metabolism during exercise and heat stress. *Journal of Applied Physiology*, *69*(3), 1040–1046. https://doi.org/10.1152/jappl.1990.69.3.1040
34. Périard, J. D., Eijsvogels, T. M. H., & Daanen, H. A. M. (2021). Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. *Physiological Reviews*, *101*(4), 1873–1979. https://doi.org/10.1152/physrev.00038.2020
35. Rowell, L. B. (1974). Human cardiovascular adjustments to exercise and thermal stress. *Physiological Reviews*, *54*(1), 75–159. https://doi.org/10.1152/physrev.1974.54.1.75
36. Rowell, L. B., Blackmon, J. R., Martin, R. H., Mazzarella, J. A., & Bruce, R. A. (1965). Hepatic clearance

of indocyanine green in man under thermal and exercise stresses. *J. Appl.Physiol.*, *20*(3), 384–394. https://doi.org/10.1152/jappl.1965.20.3.384

37. Rowell, Loring B, Brengelmann, G. L., Blackmon, J. R., Twiss, R. D., & Kusumi, F. (1968). Splanchnic blood flow and metabolism in heat-stressed man. *Journal of Applied Physiology*, *24*(4), 475–484.
38. Schlader, Z. J., Stannard, S. R., & Mündel, T. (2011). Is peak oxygen uptake a determinant of moderate duration self-paced exercise performance in the heat? *Applied Physiology, Nutrition and Metabolism*, *36*(6), 863–872. https://doi.org/10.1139/H11-111
39. Skinner, J. S., & McLellan, T. H. (1980). The Transition from Aerobic to Anaerobic Metabolism. *Research Quarterly for Exercise and Sport*, *51*(1), 234–248. https://doi.org/10.1080/02701367.1980.10609285
40. Teso, M., Colosio, A. L., & Pogliaghi, S. (2022). An Intensity-dependent Slow Component of HR Interferes with Accurate Exercise Implementation in Postmenopausal Women. *Medicine and Science in Sports and Exercise*, *54*(4), 655–664. https://doi.org/10.1249/MSS.0000000000002835
41. Tyka, A. A., Pałka, T., Tyka, A. A., Cisoń, T., & Szyguła, Z. (2009). The influence of ambient temperature on power at anaerobic threshold determined based on blood lactate concentration and myoelectric signals. *International Journal of Occupational Medicine and Environmental Health*, *22*(1), 1–6. https://doi.org/10.2478/v10001-009-0005-8
42. Tyka, A., Wiecha, S., Palka, T., Szygula, Z., Tyka, A., & Cison, T. (2010). Effects of Ambient Temperature on Physiological Responses to Incremental Exercise Test. *Journal of Human Kinetics*, *26*, 57–64. https://doi.org/10.2478/v10078-010-0049-7
43. Wasserman, K. (1984). The anaerobic threshold measurement to evaluate exercise performance. *American Review of Respiratory Disease*, *129*(2P2), S35–S40. https://doi.org/10.1164/arrd.1984.129.2p2.s35
44. Zoladz, J. A., Rademaker, A. C., & Sargeant, A. J. (1995). Non-linear relationship between O2 uptake and power output at high intensities of exercise in humans. *Journal of Physiology*, *488*(1), 211–217. https://doi.org/10.1113/jphysiol.1995.sp020959

Table 1 Power output (PO) and heart rate (HR) at which the exercise thresholds occurred in RAMP and STEP for TEMP and HOT in order of appearance

Threshold method	Power output				Heart rate			
	18°C PO (W)	36°C PO (W)	Δ %	ES	18°C HR (bpm)	36°C HR (bpm)	Δ %	ES
RAMP								
GET	198 ± 26	193 ± 27	-2.9	0.31	142 ± 9	154 ± 9 *	8.6	1.95
RCP	240 ± 33	242 ± 27	0.9	0.10	163 ± 10	171 ± 8 *	5.1	1.26
STEP								
Log-log IND	159 ± 20	155 ± 19	-2.3	0.27	130 ± 9	136 ± 7	4.7	1.04
LT_1 IND	166 ± 22	156 ± 21 *	-5.7	0.62	132 ± 8	136 ± 8	2.8	0.66
Bsln + 0.5 IND	179 ± 24	166 ± 21 *	-7.0	0.79	137 ± 8	139 ± 8	1.6	0.38
OBLA 2.0 FIX	185 ± 38	164 ± 33 *	-11.1	0.81	139 ± 11	139 ± 11	-0.4	0.07
Bsln + 1.0 IND	201 ± 31	186 ± 25 *	-7.6	0.76	146 ± 7	147 ± 8	0.8	0.22
OBLA 2.5 FIX	204 ± 40	186 ± 30 *	-8.7	0.71	147 ± 10	147 ± 9	0.2	0.04
Bsln + 1.5 IND	216 ± 33	202 ± 29 *	-6.7	0.66	152 ± 10	153 ± 9	0.8	0.19
OBLA 3.0 FIX	218 ± 40	203 ± 32 *	-6.9	0.59	152 ± 8	153 ± 9	0.9	0.24
D_{max} IND	218 ± 23	207 ± 23 *	-4.9	0.66	152 ± 9	155 ± 7	2.0	0.54
OBLA 3.5 FIX	229 ± 39	215 ± 32 *	-5.8	0.53	156 ± 9	158 ± 8	1.3	0.32
Exp-D_{max} IND	231 ± 25	217 ± 23 *	-6.0	0.81	157 ± 8	159 ± 7	1.0	0.30
OBLA 4.0 FIX	238 ± 37	226 ± 30 *	-5.0	0.50	160 ± 9	162 ± 8	1.4	0.37
$ModD_{max}$ IND	240 ± 30	226 ± 28 *	-6.0	0.71	161 ± 9	162 ± 7	0.8	0.23
Log-Poly-$ModD_{max}$ IND	241 ± 26	231 ± 25 *	-4.3	0.57	161 ± 9	164 ± 7	1.9	0.51
LT_2 IND	246 ± 31	232 ± 33 *	-5.5	0.60	162 ± 8	164 ± 7	0.7	0.21
Log-Exp-$ModD_{max}$ IND	250 ± 28	236 ± 26 *	-5.5	0.73	164 ± 9	166 ± 7	1.1	0.30

Values are mean ± standard deviation (SD) for *n* = 11 participants. Effect size (ES) is calculated and significant differences are marked (*) for $p < 0.05$. In STEP, a distinction has been made between individual (IND) an fixed value (FIX) lactate threshold methods

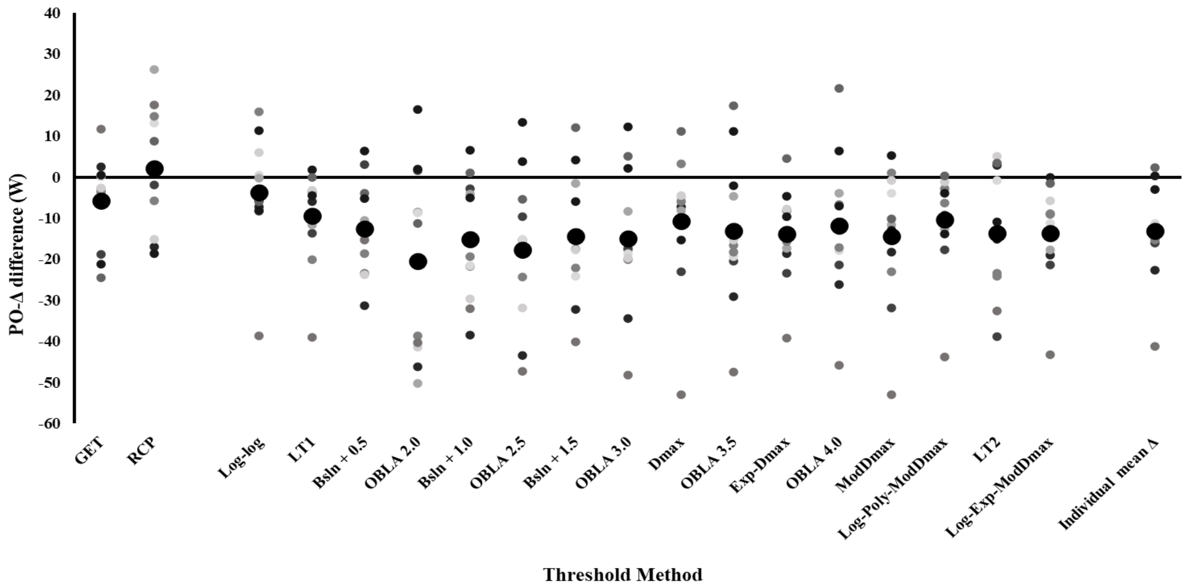

Fig. 1 Mean (big dots) and individual (small dots) difference in PO between 18°C and 36°C for all determined exercise thresholds; two respiratory thresholds, GET and RCP, in RAMP and 16 lactate thresholds in STEP. Mean difference of all exercise thresholds within the individual is displayed as Individual mean Δ.

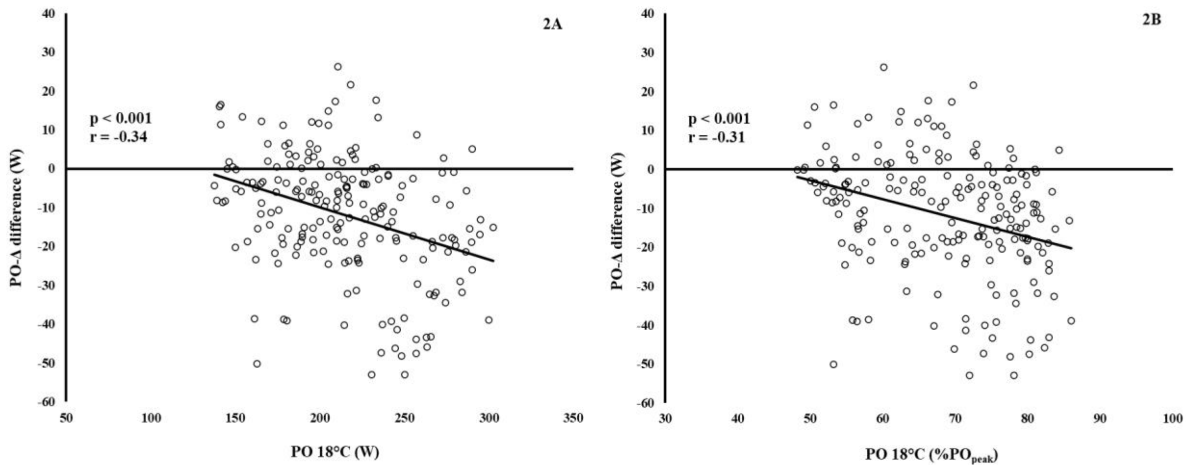

Fig. 2 Scatterplots showing the relationship between all 198 (11 participants x 18 exercise thresholds) unique thresholds determined in 18°C for (A) absolute and (B) relative PO and the PO difference between 18°C and 36°C for the determined threshold.