Relationship Between the Skin Surface Temperature Changes During Sprint Interval Testing Protocol and the Aerobic Capacity in Well-Trained Cyclists

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Short title:

Skin surface temperature changes during interval testing

Summary

The study investigated whether changes in body surface temperature in a sprint interval testing protocol (SITP) correlated with aerobic capacity in cyclists. The study involved 21 well-trained cyclists. Maximal aerobic power and maximal oxygen uptake relative to lean body mass (LBM-P_{max} and LBM-VO_{2max}, respectively) were determined by incremental exercise testing on a cycle ergometer. SITP was administered 48 hours later and involved four 30-s maximal sprints interspersed with 90-s active recovery. Body surface temperature was recorded at the temple and arm and the delta difference between baseline temperature and temperature measured immediately after the first sprint (ΔTt_1 and ΔTa_1, respectively) and 80 seconds after the fourth sprint (ΔTt_4 and ΔTa_4, respectively) was calculated. Significant correlations were found between ΔTt_4 and LBM-P_{max} and LBM-VO_{2max} ($r = 0.63$ and $r = 0.75$, respectively) with no significant change in ΔTa_1 or ΔTa_4. Body surface temperature, measured at the temple region, can be used to indirectly assess aerobic capacity during maximal sprint exercise.

Key words: body surface temperature, thermoregulation, maximal oxygen uptake, maximal sprint exercise

Introduction

Maximal oxygen uptake (VO_{2max}) is one of several physiological factors determining the endurance performance in athletes. (Levine 2008, Lucia et al. 2001, Mujika and Padilla 2001a). VO_{2max} is also important in efforts that involve single and repeated sprints due to its relationship with the rate of phosphocreatine resynthesis, phosphate concentration, and energy production via aerobic glycolysis (Girard et al. 2011, Glaister 2005). VO_{2max} is treated as a

reliable and valid measure of training-induced changes in exercise capacity (Coquart et al. 2014) and has been used as a criterion in the athlete selection process (Faria et al. 2005). Among non-athletes, VO_{2max} has been reported to reflect the efficiency of the cardiovascular (De Lorenzo et al. 2018) and respiratory system (Lopes et al. 2018) or muscular content of energy metabolism proteins (Vigelsø et al. 2016).

Another important indicator of performance among endurance athletes is the body's thermoregulatory response to exercise, which ensures that the core temperature is maintained within a temperature range which will conserve the physiological functions (Nybo and Nielsen 2001). There exists an inter-relationship between VO_{2max} and exercise-induced changes in internal temperature, in which temperature is dependent on relative exercise load, which can be expressed as a percentage of individual VO_{2max} (Yoshida et al. 1997). Hence, individuals with different levels of aerobic capacity show a similar increase in temperature during exercise at a similar relative load despite significant variation in power output. The body's thermoregulatory response to exercise is thought to be dependent, among several other factors, on the distribution of blood and several hemodynamic mechanisms. At the onset of dynamic exercise of large muscle groups, the body signals a vasoconstrictor response in non-exercising muscle (Johnson 1992, Kamon and Belding 1969, Simmons et al. 2011). This reduction in blood flow is greatest during maximal-intensity exercise (Taylor et al. 1990). Concomitantly, blood flow to working skeletal muscle is enhanced by vasodilatation in order to meet the metabolic demands of contracting muscles (Kenney and Johnson 1992). Previous research has found cutaneous blood flow to be significantly higher in trained subjects compared with untrained cohorts (Fritzsche and Coyle 2000; Johnson 1998). The changes in blood flow and distribution are easily observable by the decrease in body surface temperature in the first minutes of exercise (Kamon and Belding 1969, Simmons et al. 2011) followed by an increase in the body surface temperature with continued exercise (Kamon and Belding

1969, Simmons et al. 2011) as cutaneous blood flow increases (Johnson and Rowell 1975). The onset of perspiration and further temperature modulation is then dependent on several internal (aerobic capacity and cutaneous blood circulation) and external (ambient temperature and other environmental conditions) factors (Tankersley et al. 1991, Wingo et al. 2010).

The efficacy of the body's thermoregulatory mechanisms for eliminating excess heat, particularly those which protect brain tissue from overheating, is an important determinant of exercise performance. Body temperature among endurance athletes can reach 41.5°C during intense exercise (Racinais et al. 2019). For this reason, the inclusion of a heat acclimatization component in athlete training has been suggested in order to improve work output and increase VO_{2max} (Lorenzo et al. 2010). These physiological adaptations are explained by an increase in plasma volume and have been observed after a heat acclimation program (Lorenzo et al. 2010) or after interval (Abderrahman et al. 2013) or endurance training (Martino et al. 2002, Warburton et al. 2004). The exercise-induced expansion in plasma volume is considered by many to be beneficial as it can also enhance performance during heavy exercise by facilitating thermoregulation (Coles and Luetkemeier 2005, Nelson et al. 2008) or reducing blood viscosity (Abderrahman et al. 2013).

The above cited works suggest a relationship between thermoregulatory efficacy, VO_{2max}, and exercise performance. However, little is known about the effects of maximal exercise on changes in body surface temperature among athletes with high levels of VO_2max and maximal aerobic power. A correlation between aerobic capacity and exercise-induced changes in body surface temperature could provide a regular estimate of VO_{2max} during the training cycle. The aim of this study was to investigate this association in well-trained cyclists during a single sprint interval training session. It was assumed that the high maximal oxygen uptake allows more efficient blood flow through the cutaneous vessels, influencing the elimination of increasing temperature during sprint interval testing protocol.

Methods

Participants

Twenty-one well-trained mountain bike (MTB) cyclists aged 17–22 years participated in the study. All had been regularly training MTB for at least 3 years. Table 1 presents the basic anthropometric and the aerobic capacity characteristics of the cyclists. The study was approved by a local ethics committee and all procedures were designed to be in accordance with the Declaration of Helsinki. The participants were familiarized with the research protocol and provided their written consent to participate in the study.

Experimental design

The participants were instructed to refrain from any physical exercise 48 hours prior to the experiment. First the participants performed an incremental testing protocol (ITP) to determine aerobic capacity and then 48 h later a sprint interval testing protocol (SITP). Testing was performed in controlled laboratory conditions (ambient temperature 20.5 °C at 55–60% humidity) in the Exercise Laboratory of the University School of Physical Education (PN-EN ISO 9001:2001 certified).

a) Incremental testing protocol

Body composition was determined by ultrasound prior to testing using a Bodymetrix analyzer (Intelametrix, Brentwood, USA). Body mass (BM) was recorded in kg and body fat percentage (BF%) was determined at nine measurements sites (biceps, triceps, chest, scapula, lower back, waist, hip, thigh, and calf). Lean body mass (LBM) in kg was then calculated

using the formula *LBM = BM - (BM · %BF)*. The ITP was performed on a Lode Excalibur

Sport cycle ergometer (Lode B.V. Groningen, Netherlands) calibrated before each trial.

Starting workload was set at 50 W and increased by 50 W every 3 min until volitional

exhaustion was reached. If the participant was unable to complete an entire 3 min stage, 0.28

W was subtracted for each missing second from the work rate at that stage. The highest power

output determined in the ITP was recorded as maximal aerobic power (P_{max}).

Respiratory function was measured throughout the test by a Quark gas analyzer (Cosmed,

Milan, Italy). The gas analyzer was calibrated before each trial with a reference gas mixture of

carbon dioxide (5%), oxygen (16%), and nitrogen (79%). The participant wore a face mask

and tidal air was analyzed on a breath-by-breath basis to determine oxygen uptake (VO_2),

carbon dioxide excretion (VCO_2), and minute pulmonary ventilation (VE). Maximal oxygen

uptake (VO_{2max}) was calculated based on the composition of expired air and minute

ventilation. All measures were averaged over 30 second intervals. Maximal oxygen uptake

and maximal aerobic power were calculated relative to body mass (VO_{2max} and P_{max},

respeticely) and lean body mass (LBM-VO_{2max} and LBM-P_{max}, respectively).

Achievement of VO_{2max} was verified based on the incidence of the plateau phase in

VO_{2max} (Dempsey and Wagner 1999). The plateau response was determined using previously

established methods in which VO_2 was averaged over 15-s intervals and designated as the

period when VO_2 did not fluctuate ≤ 1.5 ml.kg-1.min-1 from the VO_{2max} (Doherty et al. 2003,

Lucia et al. 2006). Plateau VO_{2max} duration was calculated in seconds ($T_{plateau}$) and is

presented in Table 1.

b) Sprint interval testing protocol

The SITP was performed on the same Lode Excalibur Sport cycle ergometer. The test was

preceded by a warm-up begun at a workload corresponding to 40% Pmax (determined in ITP)

for 5 min and then at 50% P_{max} for 15 min. The participant then performed an active cool-

down at 10% P_{max} for 10 min followed by a 5-min rest. The test proper involved a set of four 30-s maximal cycling sprints with the participant motivated to attain peak power as quickly as possible and maintain maximum cycling cadence. Workload was individually determined at a fixed-mean crank torque of 0.8 N·m per kg of BM. Each repetition was interspersed with 90 seconds of active recovery in which workload was decreased to 30 W. Upon concluding the last repetition the participant performed an active cool-down at 30 W for 2 min.

Power output was recorded in each sprint repetition to determine the highest absolute measure of peak power in the set (P_{peak}) and average power for the entire set (P_{av}). Respiratory function was evaluated using the same procedures and equipment as in the ITP with data collected from the beginning of the first sprint until 2 min after set termination. Total oxygen uptake (VO_{2tot}) was calculated as the sum of oxygen uptake across this interval and peak oxygen uptake (VO_{2peak}) was determined as the highest absolute measure of VO_2 (Hebisz et al. 2017). The power and oxygen measures were then calculated in relation to body mass (P_{av}, P_{peak}, VO_{2tot}, VO_{2peak}) and lean body mass (LBM-P_{av}, LBM-P_{peak}, LBM-VO_{2tot}, LBM-VO_{2peak}).

Body surface temperature during the SITP was measured using a Sonel KT384 thermal imaging camera (Sonel S.A., Świdnica, Poland). The camera has a 384x288 infrared resolution at a spectral range of 8–14 μm and thermal sensitivity of 0.08° C. Data was processed using prepackaged software (Sonel ThermoAnalyzer) to extrapolate skin temperature into °C. During playback, single frames were analyzed and the average temperature across 10-pixel square targets on the temple and arm were recorded (Figure 1). The temple site was chosen due to the superficial network of blood vessels local to the temporal artery (Marano et al. 1985) whereas the forearm measurement site served as a comparative measurement. Temperature was measured while stationary after the warm-up as a baseline immediately prior to SITP (T_b), immediately after the first sprint (T_1), 80 seconds

after the first sprint (T_2), immediately after the fourth sprint (T_3), and 80 seconds after the fourth sprint (T_4). The measurement of temperature during actual sprint execution was not possible as the participants stood on the pedals and introduced significant motion blur. The delta difference between the temperature measures and baselines was then calculated separately for the temple ($\Delta Tt1$, $\Delta Tt2$, ΔTt_3, ΔTt_4) and arm (ΔTa_1 $\Delta Ta2$, $\Delta Ta3$, $\Delta Ta4$).

Statistical analysis

Data were processed using the Statistica 13.1 software package (Statsoft, USA). The distribution of the data set was checked using the Shapiro–Wilk test with normal distributions found for all measures except ΔTa_2. Means and standard deviations were calculated and one-way analysis of variance with the Duncan test administered post hoc was used to compare the differences for statistical significance. Pearson's correlation coefficients were calculated between the power and oxygen uptake measures in the ITP and SITP and ΔTt_1, ΔTa_1, ΔTt_2, ΔTa_2, ΔTt_3, ΔTa_3, ΔTt_4, and ΔTa_4. Linear regression analyses were performed for the variables that showed the strongest correlations. The significance level for all statistical procedures was set at $p < 0.05$.

Results

Temple temperature significantly increased 80 seconds after the fourth sprint (Tt_4) in comparison with temperature 80 seconds after the first sprint (Tt_2). There were no significant changes in arm temperature (Table 2). The values of power output and oxygen uptake in the ITP and SITP as absolute measures and relative to lean body mass are presented in Table 3.

The difference between the temple temperature measured 80 seconds after the first sprint and baseline (ΔTt_2) correlated positively only with relative maximal oxygen uptake measured in the ITP (LBM-VO$_{2max}$). The differences between temple temperature measured immediately after the fourth sprint (ΔTt_3) and 80 seconds after the fourth sprint (ΔTt_4) and baseline correlated positively with P$_{max}$, LBM-P$_{max}$, VO$_{2max}$ and LBM-VO$_{2max}$ obtained in ITP (Table 4 and Figure 2) as well as VO$_{2peak}$, LBM-VO$_{2peak}$, and LBM-VO$_{2tot}$ obtained in the SITP (Table 4). Regression equations were determined for LBM-P$_{max}$ (LBM-P$_{max}$ = 6.38 + 0.17 · ΔTt_4), LBM-VO$_{2max}$ (LBM-VO$_{2max}$ = 74.08 + 2.15 · ΔTt_4), and LBM-VO$_{2peak}$ (LBM-VO$_{2peak}$ = 68.46 + 2.52 · ΔTt_3). There were no statistically significant correlations between the arm temperature changes and oxygen uptake and power variables in either the ITP or SITP.

Discussion

The results obtained in the present study did not show any significant correlations between the delta change in body surface temperature measured immediately after the first sprint compared with baseline (ΔTt_1) were found with any of the measures of aerobic capacity. The lack of a correlation may be related to the relatively low stroke volume induced at this phase of the SITP due to delayed cardiac output kinetics in response to high-intensity exercise (Davies et al. 1972, Zakynthinaki 2015). In addition, this finding may also be explained by the delayed increase in cutaneous blood circulation at the onset of exercise (Johnson 1992, Simmons et al. 2011). The growing demand for oxygen by exercising skeletal muscle at the beginning of such high-intensity efforts induces the secretion of norepinephrine stimulating the post-synaptic receptors alpha$_1$ and alpha$_2$ to cause strong vasoconstriction of the cutaneous blood vessels (Johnson 1992, Johnson 1998).

Further comparisons in temple temperature showed significant correlations with both the ITP-obtained measures of aerobic capacity and SITP-based aerobic metabolism. Particularly strong correlations were obtained when comparing the delta temperatures with VO_{2max} relative to lean body mass (LBM-VO_{2max}), which may be explained by the propensity of individuals with high aerobic capacity to show enhanced metabolic function and thermoregulatory adaptations. Thermal output by contracting skeletal muscle is dependent on the metabolic response to exercise and the involvement of the aerobic and anaerobic energy pathways (Gonzalez-Alonso 2012). Sprint interval training is a particularly high energy demanding activity that severely taxes both pathways as evidenced by high levels of oxygen uptake and post-exercise lactate concentrations (Buchheit et al. 2012, Hebisz et al. 2017). The dissipation of heat generated by such intensive exercise is then modulated by several physiological mechanisms including stroke volume (Johnson 1998), blood volume (Morimoto 1990, Warburton et al. 1999), and the convective transport of heat via blood flow (Gonzalez-Alonso 2012). The above mechanisms are also strongly interrelated with VO_{2max} (Gledhill et al. 1992, Martino et al. 2002, Mujika and Padilla 2001b, Mujika and Padilla 2000, O'Neill et al. 2016), which further explains the correlations that were observed with post-exercise changes in temple surface temperature. The present results are also in concurrence with the literature on the high level of cutaneous blood flow during exercise in trained individuals (Fritzsche and Coyle 2000, Johnson 1998, Tankersley et al. 1991) and higher rectal temperature of individuals with high VO_{2max} during exercise in a warm environment (Mora-Rodriguez 2010).

The strongest correlation was observed between the delta change in temple temperature and VO_{2max} relative to lean body mass (LBM-VO_{2max}). This may be explained by the significant redistribution of blood flow in response to the heat generated by working skeletal muscle (Johnson 1992). This results in a significant increase in external carotid artery

blood flow with a concomitant decrease in internal carotid artery and vertebral artery blood flow (Ogoh et al. 2013). Wilson et al. (2006) observed markedly increased cerebral vascular resistance and reduced blood velocity in response to thermal stress. As a result, blood distribution is modified with increased extracranial blood supply to enhance the dissipation of heat via cutaneous circulation (Ogoh et al. 2013). The above adaptations are observed with a concurrent reduction in cutaneous vascular resistance due to the decrease in adrenergic innervation and, as exercise continues, increased non-adrenergic vasodilatation (Hogan 2009, Johnson 1998). Johnson (1998) had previously suggested that cutaneous blood circulation is regulated by an internal temperature threshold that modulates blood flow and the body's sensitivity to internal temperature changes particularly when exercise is performed. These mechanisms best explain the increase in temple surface temperature post-SITP in comparison with the temperature after the first sprint and the strong correlation that was observed between VO_{2max} and the changes in the temperature upon concluding the SITP. This finding suggests that VO_{2max} may be predicted via changes in temple temperature during maximal sprint exercise as the higher the maximal oxygen uptake, the greater increase in skin surface temperature in order to enhance heat dissipation during exercise.

A strong correlation was also found between the delta change in temple temperature and VO_{2peak} relative to lean body mass (LBM-VO_{2peak}). This result suggests that temple temperature can also serve as an indicator of aerobic metabolic rate during repeated sprint exercise. However, in contrast to the results of the ITP, no statistically significant relationship was observed between the delta change in temple temperature and P_{peak} or P_{av} in the SITP. The lack of any correlation may reside in the fact that repeated sprinting performance is determined to a larger extent by the anaerobic metabolism of phosphocreatine and glucose and the accumulation of metabolites in muscles than an incremental exercise test (Girard et al. 2011). Therefore, it appears that the role of cardiovascular fitness in the delivery of oxygen to

working muscle during repeated sprint exercise is less important than when performing incremental exercise (Buchheit et al. 2012, Girard et al. 2011, Hebisz et al. 2017).

Based on the present results, it can be concluded that body surface temperature during and after a single bout of sprint interval exercise can serve as an indirect method for predicting aerobic capacity, as higher VO_{2max} is associated with a greater increase in temple surface temperature during such intensive exercise. Presently, the strongest correlations were observed between VO_{2max} and the delta change in temple temperature immediately and 80 seconds after the fourth (and last) sprint repetition when compared with baseline values. Future research is needed to confirm the changes in body surface temperature in a wider range of measurement sites during and after additional exercise modalities in populations differentiated by VO_{2max}, age, and physical activity level.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

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Table 1. Anthropometric and physiological characteristics of the studied group.

Age [years]	Mass [kg]	Height [cm]	Fat tissue [%]	LBM [kg]	VO$_{2max}$ [ml·min^{-1}·kg^{-1}]	P$_{max}$ [W·kg^{-1}]	T$_{plateau}$ [s]
18.9	67.3	178.1	13.2	58.3	66.3	5.6	117.6
(2.2)	(6.6)	(5.6)	(4.1)	(7.3)	(4.6)	(0.3)	(51.8)

LBM – lean body mass, VO$_{2max}$ – maximal oxygen uptake; P$_{max}$ – maximal aerobic power; T$_{plateau}$ – time of plateau VO$_2$max; data are presented as arithmetic mean (standard deviation).

Table 2. Temple and arm temperature in subsequent measurements during sprint interval testing protocol.

	$T_b[°C]$	$T_1[°C]$	$T_2[°C]$	$T_3[°C]$	$T_4[°C]$
Temple	30.9 (2.8)	30.3 (2.9)	30.1 (2.7)	31.2 (3.1)	32.1 (2.9)*T2
Arm	29.4 (3.5)	29.7 (3.6)	30 (3.8)	30.9 (4.5)	31.5 (4.4)

T_b- the baseline temperature of the body surface, T_1 - body surface temperature immediately after the first sprint; T_2 - body surface temperature 80 seconds after the first sprint; T_3 - body surface temperature immediately after the fourth sprint; T_4 - body surface temperature 80 seconds after the fourth sprint; *T2 – $P < 0.05$ significant difference between T_4 vs. T_2; data are presented as arithmetic mean (standard deviation)

Table 3. Power output and oxygen uptake values.

Incremental testing protocol		Sprint interval testing protocol	
P_{max} [W·kg^{-1}]	5.6 (0.3)	P_{peak} [W·kg^{-1}]	19.9 (3.0)
LBM-P_{max} [W·kg^{-1}]	6.6 (0.5)	LBM-P_{peak} [W·kg^{-1}]	23.1 (3.4)
VO_{2max} [ml·min^{-1}·kg^{-1}]	66.3 (4.6)	P_{av} [W·kg^{-1}]	9.4 (0.5)
LBM-VO_{2max} [ml·min^{-1}·kg^{-1}]	76.6 (5.5)	LBM-P_{av} [W·kg^{-1}]	10.9 (0.7)
		VO_{2peak} [ml·min^{-1}·kg^{-1}]	53.3 (4.1)
		LBM-VO_{2peak} [ml·min^{-1}·kg^{-1}]	69.0 (7.0)
		VO_{2tot} [ml·kg^{-1}]	315.6 (20.8)
		LBM-VO_{2tot} [ml·kg^{-1}]	366 (33.5)

P_{max} - maximal aerobic power; VO_{2max} - maximal oxygen uptake; P_{peak} - peak power; P_{av} - average power; VO_{2peak} - peak oxygen uptake; VO_{2tot} - sum of total oxygen uptake; LBM – relative to lean body mass; data are presented as arithmetic mean (standard deviation)

Table 4. Correlations between selected power output and oxygen uptake variables and the difference in temple surface temperature measured during sprint interval testing protocol.

	ΔTt_1 [°C]	ΔTt_2 [°C]	ΔTt_3 [°C]	ΔTt_4 [°C]
Incremental testing protocol				
P_{max} [W·kg^{-1}]	0.13	0.16	0.41	0.47*
LBM-P_{max} [W·kg^{-1}]	0.16	0.39	0.55*	0.63*
VO_{2max} [ml·min^{-1}·kg^{-1}]	0.27	0.28	0.47*	0.52*
LBM-VO_{2max} [ml·min^{-1}·kg^{-1}]	0.4	0.54*	0.72*	0.75*
Sprint interval testing protocol				
P_{peak} [W·kg^{-1}]	-0.16	-0.15	-0.28	-0.28
LBM-P_{peak} [W·kg^{-1}]	-0.07	0.00	-0.09	-0.1
P_{av} [W·kg^{-1}]	-0.24	-0.15	-0.03	-0.06
LBM-P_{av} [W·kg^{-1}]	0.07	0.19	0.43	0.37
VO_{2peak} [ml·min^{-1}·kg^{-1}]	-0.08	-0.04	0.56*	0.51*
LBM-VO_{2peak} [ml·min^{-1}·kg^{-1}]	0.08	0.17	0.66*	0.61*
VO_{2tot} [ml·kg^{-1}]	-0.23	-0.18	0.34	0.26
LBM-VO_{2tot} [ml·kg^{-1}]	0.00	0.1	0.52*	0.45*

ΔTt_1 - difference between the temple temperature measured immediately after the first sprint and the baseline temperature, ΔTt_2 - difference between the temple temperature measured 80 seconds after the first sprint and the baseline temperature; ΔTt_3 - difference between the temple temperature measured immediately after the fourth sprint and the baseline temperature; ΔTt_4 - difference between the temple temperature measured 80 seconds after the fourth sprint and the baseline temperature; LBM - parameter converted into lean body mass; P_{max} - maximal aerobic power; VO_{2max} - maximal oxygen uptake; P_{peak} - peak power; P_{av} - average power; VO_{2peak} - peak oxygen uptake; VO_{2tot} - the sum of oxygen uptake; * - $P < 0.05$;

Figure 1. A single frame of a film recorded during SITP with marked fields for the temple surface temperature (R1) and arm surface temperature (R2) analysis.
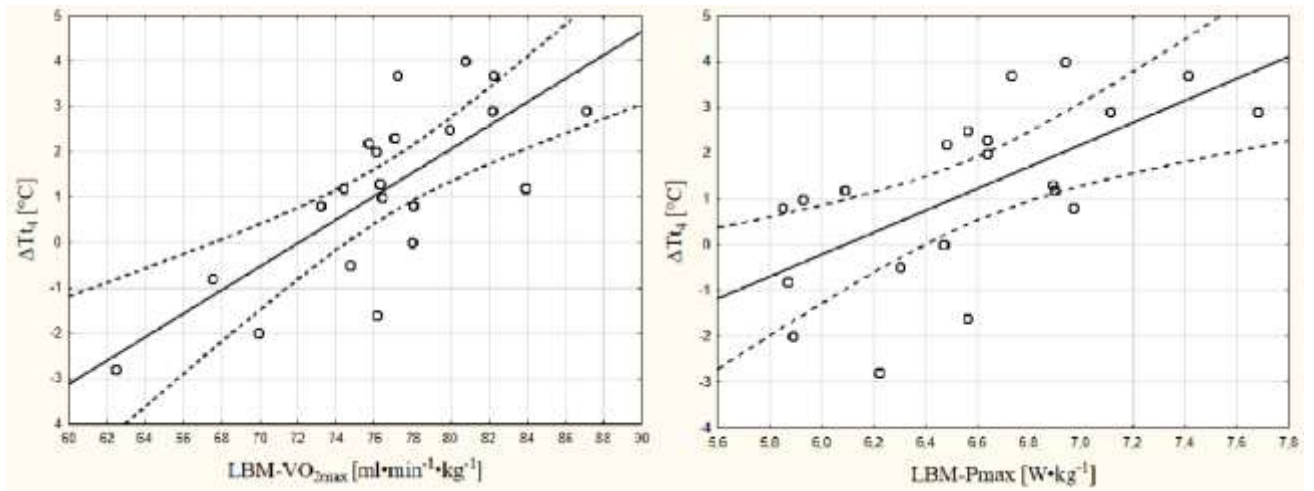
Figure 2. Plots showing the correlation between aerobic capacity, after taking the lean body mass into account, and the change in the temple surface temperature 80 seconds after the fourth sprint in relation to the baseline temperature. The aerobic capacity is represented by maximal oxygen uptake (left plot) and maximal aerobic power (right plot).