

THERMOGRAPHIC EVALUATION OF LACTATE LEVEL IN CAPILLARY BLOOD DURING POST-EXERCISE RECOVERY

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Abstract:

Changes in body temperature and in the blood lactate concentration are typical symptoms of an organism's reaction to effort. The aim of this work was to search for a relation between the temperature of the lower extremities and the blood lactate concentration. Sixteen non-training male subjects took part in the test (average age: 22.3±1.6 years). They performed maximum-height jumps from a fully knee-bent position for one minute. Their body temperature was measured by thermographic imaging and blood lactate concentration was determined at the beginning and throughout a thirty-minute recovery. An analysis of isotherms showed a strong dependence between the temperature of the front surface (FS) and back surface (BS) of the lower extremities ($r=0.83$, $p<0.05$). Immediately after exercise the temperature of the lower limbs decreased on average by about 1.44°C ($p<0.001$) and then during the recovery period rose almost to the pre-exercise value. There was a significant negative correlation ($r=-0.29$, $p<0.05$) between the temperature of lower limbs and the blood lactate concentration, both for FS ($r=-0.22$, $p<0.05$) and BS ($r=-0.23$, $p<0.05$). The results show that a maximum anaerobic effort is accompanied by a substantial drop of the temperature on surface of engaged muscles and the degree of the drop is proportional to the blood lactate concentration.

Key words: *thermography, sport, monitoring, lactate, recovery*

Introduction

It has long been known that physical exercise leads to the accumulation of lactic acid in muscle and blood. The amount of lactic acid accumulated depends on the type of exercise, its intensity and duration (Kristensen, Albertsen, Rentsch, & Juel, 2005). The maximal lactate steady state level attainable is in turn strongly correlated with the maximum anaerobic power and endurance (Beneke, 2003). Lactate measurement is used to evaluate the participation of glycolysis in the energy production during exercise; high concentrations indicate a substantial role of glycolysis (Messonnier, Freund, Bourdin, Belli, & Lacour, 1997). The blood lactate level (LA) reflects the metabolic response to exercise intensity and duration. Higher lactate level has been shown to correlate strongly with increased power (Beneke, Leithäuser, & Ochentel, 2011). Therefore, the maximum lactate concentration in the blood is a good indicator in monitoring the training process. It gives some essential information on the intensity of realized effort and the reaction of the organism, on the other hand, its measurement does not require complicated laboratory procedures and can be done easily during training (Billat, 1996; Franchini, Takito, & Bertuzzi, 2005; Beneke, et al., 2011;

Laskowski, et al., 2012). As regards training progress, the rate of lactate utilization is an important indicator, because it informs about exercise tolerance (Messonnier, et al., 2001, 2002).

One of the effects of physical effort is thermogenesis. Higher workout intensity, especially when prolonged (and thus mainly anaerobic), is connected with a transient rise of body temperature (Akimov & Sonkin, 2011). Therefore, a simple and non-invasive thermoimaging procedure can be used to roughly estimate the severity of effort expressed as the amount of lactate produced. Paradoxically, the overall increase of body temperature can be accompanied by a drop of body surface (skin) temperature due to the highly effective thermoregulatory mechanisms (Chudecka & Lubkowska, 2012). Since exercise is accompanied by changes in both blood lactate level and body temperature (Menziez, et al., 2010), these two parameters should be inter-related. It seems likely that the temperature of body surface is connected with the level of blood lactate and the speed of its utilization. Finding a relationship between these parameters should enable one to use only a single measurement to quantify exercise intensity, its tolerance, and speed of recovery. As a non-invasive procedure, temperature measurement could be used as an alternative to biochemical

determination of the blood lactate levels and give information on the training level.

A thermal image of an athlete could thus be connected both with his/her aerobic and anaerobic efficiency and post-effort regeneration (Merla, et al., 2005; Akimov, et al., 2009). There is a strong correlation between the intensity of metabolic processes and the magnitude and type of mechanical work performed, which results in heat production (Szentkuti, Kavanagh, & Grazio, 2011).

Thermography allows non-invasive monitoring of muscle activity. A substantial advantage of thermography is the possibility of conducting it at a distance, which is particularly important during competition when the contact of the coach and competitor is limited. In sport, where most events happen in dynamic conditions, continuous monitoring is essential (Coh & Sirok, 2007).

The use of thermography to estimate an athlete's performance seems reasonable because of the known close relations between the dynamics of body temperature changes and the ability of post-effort regeneration, as well as the maximum oxygen uptake (VO_{2max}) capacity. This dependence has also been confirmed for the anaerobic threshold (LT) (Akimov, et al., 2010; Akimov & Sonkin, 2011). Moreover, as reported by Temfemo, Carling, and Ahmaidi (2011), the heart rate (HR) level and the maximum power output during repeated efforts of growing intensity are also reflected in body temperature changes.

Evaluating the performance ability after various warm-up regimens, Adamczyk, Siewierski, and Boguszewski (2012) found an inverse dependence between the surface temperature of quadriceps and the height of jumps. In turn, Ding et al. (2001) claim that thermographic diagnostics allows estimation of the working muscles' metabolism. A strong and statistically significant relationship found between the maximal oxygen consumption (VO_{2max}) and the magnitude of the body surface temperature drop suggests that thermography can be an interesting alternative method to evaluate the efficiency of thermoregulatory mechanisms, effort intensity and the efficiency of recovery (Chudecka & Lubkowska, 2012).

Blood lactate concentration is the most frequently used biochemical indicator in sport practice, although this method is invasive (Weltman, et al., 1998). Despite this disadvantage, lactate monitoring is essential because it allows establishing the optimum training intensity and its constant adjustments to the changing metabolic parameters of an athlete. This is especially important in those sports where energy is mainly delivered anaerobically, resulting in high concentrations of lactate in muscles and blood (Billat, 1996). The question therefore is not whether the lactate level should be monitored, but rather by what methods this should be done to give the most useful results (Bentley, Newell,

& Bishop, 2007). Clearly, invasiveness and high cost are basic limitations of the traditional methods of measuring blood lactate. If a good correlation could be shown between blood lactate level and body surface temperature, then simple thermography could be used instead of complicated measurements, thereby greatly enhancing the ease of monitoring the training. Based on this assumption, the aim of the present study was to establish the relation between temperature of the body surface and the concentration of lactate in the capillary blood after anaerobic exercise.

Methods

Participants

Only non-trained adults (with incidental moderate physical activity), healthy male volunteers, were included in the study. The exclusion criteria were: obesity (BMI above 25), thick hair, scars, tattoos until the finish of tissue reconstruction, less than three days after cold, and alcohol consumption less than 24 hours before the examination. Finally, sixteen non-trained men were enrolled in the study. Their average age was 22.3 years (± 1.6), body height 184.1 centimetres (± 7.1) and body mass 81.2 kg (± 8.3). All had the BMI within norm (21.50–24.98).

Procedure

The trial was conducted without warm-up in order not to affect blood lactate level (LA) at rest. The participants were asked to perform maximum-height jumps from a fully knee-bent position for one minute without rest (Rittweger, Mutschelknauss, & Felsenberg, 2003). Then, immediately after completing the task and through a thirty-minute recovery period in a sitting position (they stood up for measurements) on a chair, their body temperature was monitored by a thermal camera. Such an example can be found in classic thermal imaging paper of Torii, Yamasaki, Sasaki, and Nakayama (1992). While being in the sitting position, the participants were asked to pay attention not to touch the chair with the analysed parts of the body (especially buttocks and thighs), in order not to influence the blood flow and impact the body surface temperature. Ten thermograms of the front (FS) and back (BS) surface of lower limbs for each subject were taken in a standing position. The front surface was scanned from the deflection in the hip joint to the ankle (without knee) and the back surface from the gluteal folds to the ankle (including popliteal fossa) (Figure 1). No clothing was worn on the scanned parts. The average temperature of the measurement area was used for further analysis. Along with average temperature analysis in the defined area, the hottest and the coldest points of image were observed.

We used a MobIR M3 camera (Wuhan Guide, China) with a thermal sensitivity of $\leq 120mk$, an

error of $\pm 2\%$ reading in Celsius degrees ($^{\circ}\text{C}$), a resolution of 160×120 pixels, and the IrAnalyser computer software. The camera had a valid certificate. Additionally, the camera was calibrated for reproducibility and accuracy of readings according to the Glamorgan's guidelines (Ammer, 2008). Care was taken to ensure that the camera was perpendicular to the scanned surface. Distortion errors and regions of the limb contour were excluded from analysis and only the surfaces marked in Figure 1 were subjected to automatic integration.

The distance between the camera and the photographed object was 1 m, the ambient temperature was $22\text{--}24^{\circ}\text{C}$ and humidity $48\text{--}50\%$. The humidity was measured with a hygrometer before each thermography (Jones, 1998).

Before the exercise the subjects adapted to ambient conditions for 15 minutes, with the lower limbs unclothed, to achieve thermal equilibrium with environment conditions.



Figure 1. The front (a) and back (b) thermogram with marked zones for automatic analysis.

Blood lactate and body temperature were measured at rest (after previous adaptation) and then at 1st, 3rd, 6th, 9th, 12th, 15th, 20th, 25th and 30th minute of recovery (Baldari, Videira, Madeira, Sergio, & Guidetti, 2005). Blood lactate (LA) concentration was measured in a capillary earlobe sample and analysed with a Dr Lange LP 420 photometer (Germany) (Medbø, Mamen, Holt Olsen, & Evertsen, 2000).

Participants were informed of any risks and provided their written informed consent. The study was approved by the Local Research Ethics Committee.

Statistical analyses

The correlation between temperature changes and lactate level was established by means of the Pearson's coefficient. The null hypothesis for normality of data was defined through Kolmogorov-Smirnov test. Changes between values of consecutive measurements were evaluated by Wilcoxon test. P values of $\leq .05$ were assumed as statistically significant. Statistical analyses were conducted using STATISTICA for Windows (data analysis software system) – StatSoft, Inc. (2009) version 9.0.

Results

Following the exercise the temperature of the front (FS) and back surface (BS) of lower extremities dropped, respectively, by about 1.69° and 1.19°C (readings after one-minute rest). Body surface temperature gradually increased to almost the resting state values after thirty minutes (Table 1). The FS temperatures showed a more uniform grad-

Table 1. Temperature of the front and back surface of lower limbs in consecutive measurements (mean values); significant p values are bolded

Front surface (FS)	p	Time	Back surface (BS)	p
34.66 \pm 1.07	.42 (REST vs 30')	REST	34.61 \pm 0.95	.60 (REST vs 30')
32.97 \pm 1.63	.000 (0' vs 1')	1'	33.42 \pm 1.59	.000 (0' vs 1')
33.17 \pm 1.48	.13 (1' vs 3')	3'	33.44 \pm 1.27	.88 (1' vs 3')
33.42 \pm 1.81	.10 (3' vs 6')	6'	33.26 \pm 1.35	.04 (3' vs 6')
33.48 \pm 1.77	.73 (6' vs 9')	9'	33.15 \pm 1.36	.43 (6' vs 9')
33.81 \pm 1.75	.009 (9' vs 12')	12'	33.38 \pm 1.35	.02 (9' vs 12')
33.86 \pm 1.55	.60 (12' vs 15')	15'	33.54 \pm 1.29	.052 (12' vs 15')
34.04 \pm 1.37	.20 (15' vs 20')	20'	33.66 \pm 1.29	.32 (15' vs 20')
34.20 \pm 1.12	.36 (20' vs 25')	25'	34.21 \pm 1.27	.004 (20' vs 25')
34.51 \pm 1.16	.03 (25' vs 30')	30'	34.52 \pm 1.18	.03 (25' vs 30')

ual increase than did the BS values. Both temperatures were highly correlated ($r=.83$, $p<.05$). The highest ratio of temperature recovery was observed between the ninth and twelfth minute, especially for the FS, and at the end of the rest period. The differences between the FS and BS temperatures were statistically non-significant, except for the first measurement after exercise, when the difference (0.45°C) was highly significant ($p=.001$).

The concentration of lactic acid changed substantially throughout the experiment (Table 2). On average, regeneration started already between the third and sixth minute of rest, but in some subjects we observed LA build-up even up to the ninth minute. The thirty-minute rest period proved insufficient to bring down the LA level to control (resting state) values (Figure 2). The rate of LA re-utilization was the highest and highly statistically significant between the ninth and twelfth minute of recovery. The drop in the previous interval (6th to 9th minute), while even higher, was only marginally significant. After the exercise performance BS temperature was higher than FS until the LA started to drop.

The average temperature of the lower extremities and the blood lactate concentration were weakly, but significantly negatively correlated ($r=-.29$, $p<.05$) (Figure 3). This was also true for the FS and BS temperatures analysed separately versus LA concentration

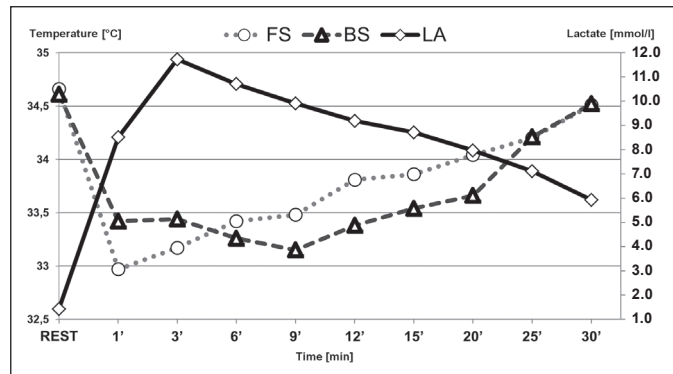


Figure 2. Comparison of the blood lactate level and thermal evolution at rest, immediately after the exercise and during the 30-minute recovery period.

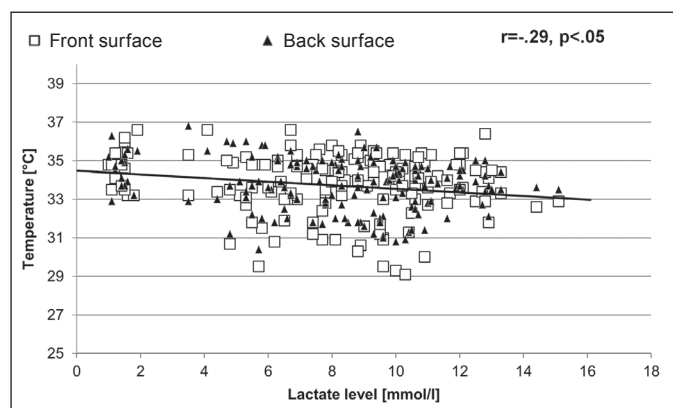


Figure 3. Dependence between the lactate concentration in capillary blood and surface temperature of lower limbs.

Table 2. Lactate concentration in capillary blood in consecutive measurements (mean values); significant p values are bolded

TIME	M	SD	Min	Max	p
REST	1.42	0.25	1.0	1.9	.000 (REST vs 30')
1'	8.51	2.51	4.8	14.4	.000 (0' vs 1')
3'	11.73	1.63	9.0	15.1	.000 (1' vs 3')
6'	10.71	1.27	9.2	12.8	.001 (3' vs 6')
9'	9.91	1.84	6.3	13.3	.04 (6' vs 9')
12'	9.19	1.78	5.8	12.1	.000 (9' vs 12')
15'	8.72	1.84	5.8	12.0	.004 (12' vs 15')
20'	7.97	1.76	4.9	11.6	.000 (15' vs 20')
25'	7.11	1.65	4.7	9.9	.000 (20' vs 25')
30'	5.93	1.73	3.5	9.4	.000 (25' vs 30')

($r=-.22$, $p<.05$ and $r=-.23$, $p<.05$, respectively). It is notable that the period between the ninth and twelfth minute of recovery was the most significant interval during recovery as evaluated both by temperature normalization and the blood lactate utilization.

Discussion and conclusions

In the conducted study the thermal response to the exertion of the tested subjects was a substantial fall of the lower limbs' surface temperature, which to the greatest extent took place immediately after the end of exercise. The analysis of thermograms showed that this drop was the strongest in the front part of the thigh which was the most loaded muscle in that type of exercise (Comfort & Kasin, 2007). Moreover, during the exercise the subjects reported painfulness of thigh muscles. A drop of body surface temperature during physical exercise has already been studied with reference to different sports (Merla, Mattei, Di Donato, & Romani, 2010; Chudecka & Lubkowska, 2010; Adamczyk, et al., 2012; Chudecka & Lubkowska, 2012). This drop is explained, among other things, by increased efficiency of thermoregulation, cooling by air flow, perspiration, and changes in the dynamics of blood sup-

ply needed to support the working muscles. Thus, the lowering of skin surface temperature is a typical thermal reaction to exercise (Torii, et al., 1992; Yanagimoto, et al., 2003). The higher the intensity of effort, the greater changes in body surface temperature are to be expected (Coh & Sirok, 2007).

Although we found a statistically significant relationship between the body surface temperature of lower limbs and the blood lactate level, it was rather weak and could only be discerned due to a high number of measurements (160) taken for analysis. The correlation coefficient was relatively low ($r=-.29$) and the lactate level was explained in only about 10% (value of determination coefficient R^2) by the surface temperature of lower limbs. Therefore, although the results were statistically significant, they must be cautiously interpreted.

Many authors reported that the most effective drop of blood lactate level can be expected in the first ten minutes of recovery (Bangsbo, Gollnick, Graham, & Saltin, 1991; Greenwood, Moses, Bernardino, Gaesser, & Weltman, 2008; Ali Rasooli, Koushkie Jahromi, Asadmanesh, & Salehi, 2012). We confirmed that observation by finding the most significant LA and temperature changes between the ninth and twelfth minute of rest. This is why we recommend that in that period of recovery thermography measurements used to evaluate the efficiency of recovery would be most valid. Significant warming up of the skin temperature, as well as the drop of LA should be observed at that time. Thirty minutes of recovery should allow the body surface temperature to return to the state at rest.

Anyway, the relation found between the body surface temperature and lactate level has no reference in the literature concerning humans. Interestingly, similar observations were made on animals. Berkman et al. (2011) observed the lowering of skin temperature during progressive effort, as well as relations between temperature and lactate concentration in racing horses. The authors explain that phenomenon by the reduction of blood perfusion during anaerobic exercise with the simultaneous increase of blood lactate concentration. The temperature of the skin then returned to the one in the resting state and, as a physiological consequence of the recovery, the blood lactate level dropped. Analogies in response to exercise may be due to similar physiological and biochemical thermoregulation mechanisms in mammals.

Blood lactate level and body surface temperature seem to be naturally connected - at first because both parameters' changes are a response to exercise. Moreover, lactate transformation, especially during recovery, is temperature-related, e.g. through lactate dehydrogenase (Zuber, 1988). During exercise the core temperature decreases as the muscle temperature increases (we observed the lowering of surface temperature as an effect of losing

excess heat) because of the increase in peripheral limb blood flow that is, importantly, further enhanced by exercise (Crampton, Egaña, Donne, & Warmington, 2014). Furthermore, vascular occlusion during exercise reinforces the effect of lowering the surface temperature. At the same time we observed a lactate efflux from muscles into the blood as a response to anaerobic high-intensity effort. Both LA and skin temperature variations refer to changes in tissue metabolism, which might explain the observed connections between both variables (Wirtz, Wahl, Kleinöder, & Mester, 2014).

When analysing these results one must remember that the blood lactate concentration is only an approximate measure of muscle lactate, because only a part of it is transported (the hydrogen ion is used to restore ATP) (Spriet, Howlett, & Heigenhauser, 2000). Furthermore, the efficiency of lactate release from muscles to blood depends on capillary density because increased surface area facilitates the exchange by reducing the distance between the site of lactate production and the circulatory system (Messonnier, et al., 2002).

The dependence between body temperature and blood lactate level reported here allows one to propose the use of thermovision as an aid in training management. The process of post-effort regeneration reflected by lactate utilization in the examined group was first connected with the decrease and then with the increase of body temperature, and finally with its return to resting values. Of course, one should keep in mind that not only glycolytic anaerobic exercise will cause a fall in skin temperature. Therefore, the temperature does not directly inform about lactate concentration. However, observation of recovery efficiency with thermal imaging is possible. It seems that during recovery an opposite process to that described earlier for the period of exercise takes place; namely, the circulation returns to its pre-exercise patterns thereby heating the skin surface, especially in the limbs (Torii, et al., 1992; Schlader, Stannard, & Mundel, 2010). This may reflect the combined effect of an increase in metabolism and the restoration of normal muscle temperature resulting in the distribution of heat from the active musculature to the core (Crampton, et al., 2014). A direct measurement of peripheral blood flow is difficult, and popular methods have inherent limitations, including interference with normal blood flow (Games & Sefton, 2011). Infrared thermography gives a valid and reliable (Burnham, McKinley, & Vincent, 2006), non-invasive alternative that does not interfere with blood flow (Wright, Kroner, & Draijer, 2006). Thus, it may provide an improved method of evaluating muscle metabolism by assessing muscle tissue blood perfusion and oxygen utilization. Thermal observation of the competitor having a rest after the effort can be an indirect non-invasive manner of estimating the effectiveness

of recovery. This method could supplement other known measurements like HR or lactate concentration applied to evaluate recovery efficiency. We are aware, however, that this refers only to passive recovery, because the active one would probably cause a slower temperature rise. Other methods aiding recovery after thermal and cardiovascular load, e.g. cold water immersion, could also change thermal reaction (Pournot, et al., 2011; Pointon, Duffield, Cannon, & Marino, 2012). Other factors can possibly influence recovery, e.g. listening to motivational music during non-structured recovery from intense exercise leads to increased activity and faster lactate clearance (Eliakim, Bodner, Eliakim, Nemet, & Meckel, 2012). This simultaneously suggests the possible directions for further scientific exploration.

An important prerequisite for the use of thermography in training monitoring is experience from its application in sports medicine. We know that application possibilities are connected, for example, with detection of injuries or an inflammatory process (Selfe, Sutton, & Hardaker, 2010; Piñonosa, Sillero-Quintana, Milanović, Coterón, & Sampedro, 2013). Introduction of novel non-invasive diagnostics methods is valuable because they broaden the application possibilities in everyday sports practice. Additionally, the problems of ethical nature are avoided, e.g. those related to research on children. Therefore, non-invasive methods aiding the selection of training intensity have been used in training practice for a long time because of their low cost and higher psychological comfort of com-

petitors (Swensen, Harnish, Beitman, & Keller, 1999; Klusiewicz, & Cempa, 2011). The method proposed here is superior to many other because it does not generate costs of each measurement and can be used throughout a contest while other measurement modes require the interruption of an effort.

In conclusion, one ought to ascertain that the thermal reaction to performance is the fall of the temperature of the body surface tested. After exercise the temperature of the back surface was higher than of the front side of the lower extremities until we have noticed LA drop. A higher concentration of lactate, accompanied by a lower surface temperature of legs, was found in the analysed group. The negative correlation between the examined parameters was statistically significant ($p < .05$), but was too weak to predict the lactate level from the surface temperature with certainty. However, throughout the thermography we could not track the LA changes with high accuracy, so we believe that the proposed method can serve as an indirect, non-invasive estimation tool of the effectiveness of post-effort recovery. We recommend that the time around the tenth minute of recovery be most valid for thermography measurements. Significant warming up of body surface, as well as blood lactate drop should be observed at that time. The obtained results require further verification because the study was limited to untrained subjects and was done on a rather small group. Trained athletes are expected to have more effective mechanisms of lactate utilization (Messonnier, et al., 2001), especially as a result of endurance training.

References

- Adamczyk, J.G., Siewierski, M., & Boguszewski, D. (2012). Correlation of musculus quadriceps femoris temperature and power measured by vertical jump height. *Teoriya i Praktika Fizicheskoy Kultury*, 7, 94-97.
- Akimov, E.B., Andreev, R.S., Arkov, V.V., Kirdin, A.A., Saryanc, V.V., Sonkin, V.D., & Tonevitsky, A.G. (2009). Thermal "portrait" of sportsmen with different aerobic capacity. *Acta Kinesiologiae Universitatis Tartuensis*, 14, 7-16.
- Akimov, E.B., Andreev, R.S., Kalenov, I.N., Kirdin, A.A., Sonkin, V.D., & Tonevitsky, A.G. (2010). Human temperature portrait and its relations with aerobic working capacity and the level of blood lactate. *Fiziologia Cheloveka*, 36(4), 89-101.
- Akimov, E.B., & Sonkin, V.D. (2011). Skin temperature and lactate threshold during muscle work in sportsmen. *Fiziologia Cheloveka*, 37(5), 120-128.
- Ali Rasooli, S., Koushkie Jahromi, M., Asadmanesh, A., & Salehi M. (2012). Influence of massage, active and passive recovery on swimming performance and blood lactate. *Journal of Sports Medicine and Physical Fitness*, 52(2), 122-127.
- Ammer, K. (2008). The Glamorgan Protocol for recording and evaluation of thermal images of the human body. *Thermology International*, 18, 125-129.
- Baldari, C., Videira, M., Madeira, F., Sergio, J., & Guidetti, L. (2005). Blood lactate removal during recovery at various intensities below the individual anaerobic threshold in triathletes. *Journal of Sports Medicine and Physical Fitness*, 45(4), 460-466.
- Bangsbo, J., Gollnick, P.D., Graham, T.E., & Saltin B. (1991). Substrates for muscle glycogen synthesis in recovery from intense exercise in man. *Journal of Physiology*, 1, 289-295.
- Beneke, R. (2003). Methodological aspects of maximal lactate steady state – Implications for performance testing. *European Journal of Applied Physiology*, 89(1), 95-99.

- Beneke, R., Leithäuser, R.M., & Ochentel, O. (2011). Blood lactate diagnostics in exercise testing and training. *International Journal of Sports Physiology Performance*, 6(1), 8-24.
- Bentley, D.J., Newell, J., & Bishop, D. (2007). Incremental exercise test design and analysis: Implications for performance diagnostics in endurance athletes. *Sports Medicine*, 37(7), 575-586.
- Berkman, C., Albernaz, R.M., Basile, R.C., de Lacerda-Neto, J.C., de Queiroz-Neto, A., & de Camargo Ferraz, G. (2011). Exercício em esteira não elevou a temperatura do casco de equinos. [Exercise on treadmill did not enhance the temperature of the equine hoof. In Portuguese.] *Ciência Rural, Santa Maria*, 41(8), 1398-1404.
- Billat, L.V. (1996). Use of blood lactate measurements for prediction of exercise performance and for control of training. Recommendations for long-distance running. *Sports Medicine* 22(3), 157-175.
- Burnham, R.S., McKinley, R.S., & Vincent, D.D. (2006). Three types of skin-surface thermometers: A comparison of reliability, validity, and responsiveness. *American Journal of Physical Medicine & Rehabilitation*, 85(7), 553-558.
- Chudecka, M., & Lubkowska, A. (2010). Temperature changes of selected body's surfaces of handball players in the course of training estimated by thermovision, and the study of the impact of physiological and morphological factors on the skin temperature. *Journal of Thermal Biology*, 35(8), 379-385.
- Chudecka, M., & Lubkowska, A. (2012) The use of thermal imaging to evaluate body temperature changes of athletes during training and a study on the impact of physiological and morphological factors on skin temperature. *Human Movement*, 13(1), 33-39.
- Coh, M., & Sirok, B. (2007). Use of the thermovision method in sport training. *Facta Universitatis. Physical Education and Sport*, 5(1), 85-94.
- Comfort, P., & Kasin P. (2007). Optimizing squat technique. *Strength & Conditioning Journal*, 29(6), 10-13.
- Crampton, D., Egaña, M., Donne, B., & Warmington, S. A. (2014). Including arm exercise during a cold water immersion recovery better assists restoration of sprint cycling performance. *Scandinavian Journal of Medicine & Science in Sports*, 24(4), 290-298.
- Ding, H., Wang, G., Lei, W., Wang, R., Huang, L., Xia, Q., & Wu, J. (2011). Non-invasive quantitative assessment of oxidative metabolism in quadriceps muscles by near infrared spectroscopy. *British Journal of Sports Medicine*, 35(6), 441-444.
- Eliakim, M., Bodner, E., Eliakim, A., Nemet, D., & Meckel, Y. (2012). Effect of motivational music on lactate levels during recovery from intense exercise. *Journal of Strength and Conditioning Research*, 26(1), 80-86.
- Franchini, E., Takito, M.J., & Bertuzzi, R.C.M. (2005). Morphological, physiological and technical variables in high-level college judoists. *Archives of Budo*, 1, 1-7.
- Games, K.E., & Sefton, J.M. (2011) Whole-body vibration influences lower extremity circulatory and neurological function. *Scandinavian Journal of Medicine & Science in Sports*, 23(4), 516-523.
- Greenwood, J.D., Moses, G.E., Bernardino, F.M., Gaesser, G.A., & Weltman A. (2008). Intensity of exercise recovery, blood lactate disappearance and subsequent swimming performance. *Journal of Sports Sciences*, 26, 29-34.
- Jones, B.F. (1998). A reappraisal of the use of thermal image analysis in medicine. *IEEE Transactions on Medical Imaging*, 17, 1019-1027.
- Klusiewicz, A., & Cempa, W. (2011). Verification of anaerobic threshold indicators for cross-country skiers in natural conditions. *Polish Journal of Sport and Tourism*, 18, 300-307.
- Kristensen, M., Albertsen, J., Rentsch, M., & Juel, C. (2005). Lactate and force production in skeletal muscle. *The Journal of Physiology*, 562(2), 521-526.
- Laskowski, R., Kujach, S., Smaruj, M., Grzywacz, T., Łuszczuk, M., Adam, M., & Ziemann, E. (2012). Lactate concentration during one-day male judo competition: A case study. *Archives of Budo*, 8(1), 51-57.
- Medbø, J.I., Mamen, A., Holt Olsen, O., & Evertsen, F. (2000). Examination of four different instruments for measuring blood lactate concentration. *Scandinavian Journal of Clinical and Laboratory Investigation*, 60(5), 367-380.
- Menzies, P., Menzies, C., McIntyre, L., Paterson, P., Wilson, J., & Kemi, O.J. (2010). Blood lactate clearance during active recovery after an intense running bout depends on the intensity of the active recovery. *Journal of Sports Sciences*, 28(9), 975-982.
- Merla, A., Iodice, P., Tangherlini, A., Michele, G.D., Romualdo, S.D., Saggini, R., & Romani, G.L. (2005). Monitoring skin temperature in trained and untrained subjects throughout thermal video. *Proceedings of the 27th Annual International Conference EMBS* (pp. 1684-1686). Shanghai: IEEE.
- Merla, A., Mattei, P., Di Donato, L., & Romani G. (2010). Thermal imaging of cutaneous temperature modifications in runners during graded exercise. *Annals of Biomedical Engineering*, 38(1), 158-163.
- Messonier, L., Freund, H., Bourdin, M., Belli, A., & Lacour, J.R. (1997). Lactate exchange and removal abilities in rowing performance. *Medicine and Science in Sports and Exercise*, 29(3), 396-401.
- Messonier, L., Freund, H., Denis, C., Dormois, D., Dufour, A.B., & Lacour, J.R. (2002). Time to exhaustion at VO_{2max} is related to the lactate exchange and removal abilities. *International Journal of Sports Medicine*, 23(6), 433-438.
- Messonier, L., Freund, H., Féasson, L., Prieur, F., Castells, J., Denis, C., Linossier, M.T., Geysant, A., & Lacour, J.R. (2001). Blood lactate exchange and removal abilities after relative high-intensity exercise: Effects of training in normoxia and hypoxia. *European Journal of Applied Physiology*, 84(5), 403-412.
- Piñonosa, S., Sillero-Quintana, M., Milanović, L., Coterón, J., & Sampedro, J. (2013). Thermal evolution of lower limbs during a rehabilitation process after anterior cruciate ligament surgery. *Kinesiology* 45(1), 121-129.

- Pointon, M., Duffield, R., Cannon, J., & Marino, F.E. (2012). Cold water immersion recovery following intermittent-sprint exercise in the heat. *European Journal of Applied Physiology*, 112(7), 2483-2494.
- Pournot, H., Bieuzen, F., Duffield, R., Lepretre, P.M., Cozzolino, C., & Hauswirth, C. (2011). Short-term effects of various water immersions on recovery from exhaustive intermittent exercise. *European Journal of Applied Physiology*, 111(7), 1287-1295.
- Rittweger, J., Mutschelknauss, M., & Felsenberg, D. (2003). Acute changes in neuromuscular excitability after exhaustive whole body vibration exercise as compared to exhaustion by squatting exercise. *Clinical Physiology & Functional Imaging*, 23(2), 81-86.
- Schlader, Z.J., Stannard, S.R., & Mundel, T. (2010). Human thermoregulatory behavior during rest and exercise – A prospective review. *Physiology & Behavior*, 99(3), 269-275.
- Selfe, J., Sutton, Ch., & Hardaker, N.J. (2010). Anterior knee pain and cold knees: A possible association in woman. *The Knee*, 17(5), 319-323.
- Spriet, L.L., Howlett, R.A., & Heigenhauser, G.J.F. (2000). An enzymatic approach to lactate production in human skeletal muscle during exercise. *Medicine & Science in Sports & Exercise*, 32(4), 756-763.
- Swensen, T.C., Harnish, C.R., Beitman, L., & Keller, B.A. (1999). Noninvasive estimation of the maximal lactate steady state in trained cyclists. *Medicine & Science in Sports & Exercise*, 31(5), 742-746.
- Szentkuti, A., Kavanagh, H.S., & Grazio, S. (2011). Infrared thermography and image analysis for biomedical use. *Periodicum Biologorum*, 113(4), 385–392.
- Temfemo, A., Carling, C., & Ahmaidi, S. (2011). Relationship between power output, lactate, skin temperature, and muscle activity during brief repeated exercises with increasing intensity. *Journal of Strength and Conditioning Research*, 25(4), 915-921.
- Torii, M., Yamasaki, M., Sasaki, T., & Nakayama, H. (1992). Fall in skin temperature of exercising man. *British Journal of Sports Medicine*, 26(1), 29-32.
- Weltman, A., Weltman, J.Y., Kanaley, J.A., Rogol, A.D., Veldhuis, J.D., & Hartman, M.L. (1998). Repeated bouts of exercise alter the blood lactate-RPE relation. *Medicine & Science in Sports & Exercise*, 30(7), 1113-1117.
- Wirtz, N., Wahl, P., Kleinöder, H., & Mester, J. (2014). Lactate kinetics during multiple set resistance exercise. *Journal of Sports Science and Medicine*, 13, 73-77.
- Wright, C.I., Kroner, C.I., & Draijer, R. (2006). Non-invasive methods and stimuli for evaluating the skin's microcirculation. *Journal of Pharmacological and Toxicological Methods*, 54(1), 1–25.
- Yanagimoto, S., Kuwahara, T., Zhang, Y., Koga, S., Inoue, Y., & Kondo, N. (2003). Intensity-dependent thermoregulatory responses at the onset of dynamic exercise in mildly heated humans. *American Journal of Physiology – Regulatory, Integrative, and Comparative Physiology*, 285(1), 200-207.
- Zuber, H. (1988). Temperature adaptation of lactate dehydrogenase: Structural, functional and genetic aspects. *Biophysical Chemistry*, 29(1-2), 171-179.

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