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Review

Effects of Heat and Humidity on Cycling Training and Performance: A Narrative Review

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Abstract: Heat and humidity are commonly listed as some of the most relevant environmental factors that may reduce cycling performance. Further, global warming may produce, in the upcoming years, a dramatic increase in heat stress during outdoor sporting events such as cycling. Accordingly, the interest in the assessment of the effects of heat stress has been recently accompanied by relevant scientific production regarding the true utility of training in hot and humid conditions for the optimization of performance both under thermoneutral and extreme environmental conditions. Current scientific evidence, as summarized in this narrative review, shows that cycling performance is severely impaired by heat and humidity. Specific heat training protocols and their effects are also reviewed to show their great potential to limit this impairment and also to potentially improve performance in thermoneutral environments.

Keywords: temperature, humidity, endurance, bike, cycling, performance.

1. Effects of heat and humidity on cycling performance

The effects of temperature on performance can be explained by the combination of 4 factors: air temperature, relative humidity, wind and solar radiation. The temperature of the human body ranges between 36.5 and 37.5 °C under normal conditions. The body temperature increases with exercise, and more notoriously when the external temperature is high. Exercise performed in hot environments (30-40 °C) represents a state of stress for the organism that entails a decrease in performance of around 6-16%. Some of the accompanying symptoms involve chills, muscle weakness and/or disorientation. Due to the high environmental temperature and the consequent rise in body temperature, the compensatory physiological mechanisms are activated to avoid the decline in sports performance. However, upon reaching extreme temperatures (41°C to 41.7°C), fatigue management becomes a very difficult task as the sweating capacity and hypothalamic control deteriorate notoriously, producing a cessation of physical activity as the final outcome (Heathcote et al., 2018). Racinais et al. (2018) evaluated body temperatures in 40 professional cyclists with environmental conditions of around 37°C and a relative humidity of around 25%. The results showed that 85% of the subjects exceeded 39°C of internal body temperature, very close to the 40°C commonly reported as the maximal value that can be sustained in trained athletes. It has also been shown that those athletes who begin the activity at a higher core temperature have a smaller margin to reach that maximum temperature (40°C) and therefore, they achieve a shorter test time compared to those who start at lower body temperatures (Noakes, 2012). The effects of heat stress in competitive cyclists are relatively common: Racinais et al. (2020)

assessed preparation strategies followed by elite cyclists for the World Road Cycling Championships in Qatar, 2016, where temperatures of about 36°C and a relative humidity of 24.6% were reached. The researchers observed that 22% of respondents had suffered heat illness symptoms in the 10 days prior to the Championship, the most common being headaches (56%) and gastrointestinal problems (32%).

The effect of high temperatures is greatly influenced by the % relative humidity of the air. Dry heat occurs with relative humidity of less than 45% and humid heat with temperatures greater than said value. In this line, the late studies performed by Fox et al. (1967) and Eichna et al. (1945) observed that acclimatization in dry heat improves exercise in humid heat and vice versa, thus both protocols seem effective. However, higher surface temperatures will be reached when the skin is exposed to humid heat due to the greater difficulty in evaporation, thus this seems, from a theoretical viewpoint, a more demanding protocol. This was also observed in the study by Baillot et al. (2021) where they evaluated the impact of dry heat vs wet heat temperatures on the performance of 10 cyclists and triathletes acclimatized to tropical climates who performed a 20-kilometer time trial in neutral, dry and humid conditions. They observed that the rate of perceived exertion was greater in humid heat. There was also a greater rate of weight loss, skin temperature was higher, and heart rate was significantly higher in both heat conditions than in neutral temperatures. The time trial performance was also better in the dry heat rather than the humid heat group. The most coherent action would be to implement one type of heat training or another according to the competition demands and expected environmental factors. Even so, it could be a good option to combine both methods to further stress the cardiovascular and thermoregulatory system and achieve greater adaptations. Regardless of the type of heat training implemented, both will result in the so-called "cardiac drift" (Nybo, 2010), which consists of a decrease in stroke volume and an increase in heart rate, which is an effect of loss of plasma volume due to sweating and an attempt to cool and maintain body temperature by directing a greater amount of blood to the skin.

In general, most studies report decreases in performance when training at high temperatures: Tatterson et al. (2000) investigated the effect of heat stress on the physiological responses and performance of elite road cyclists, with a sample of 11 participants who completed two 30-minute time trials, one at 32°C and 60% relative humidity and another at 23°C and 60% relative humidity. The results showed that the temperature of the skin, sweat rate and blood lactate production were greater with high temperatures, and the power was reduced due to the increase in body temperature, so they concluded that, in non-acclimatized elite road cyclists, when temperatures rise above 30°C, there is an expected decrease in performance of 6-7%. Later, Girard et al. (2013) assessed sprint performance with isometric contractions of the knee extensors, both in hot and thermoneutral conditions. They reported improvements in power output in warm conditions during the initial sprint, although there was a general decrease during subsequent sprints, which also occurred in neutral conditions. Skin and core temperatures were higher in the heat, demonstrating that, in the absence of hyperthermia, temperature does not affect fatigue resistance in the repeated sprint test, because the decrease in power was similar in both conditions.

In summary, cycling performance is decreased under hot and humid conditions due to impairments in the thermoregulatory mechanisms, a phenomenon that occurs both during dry and humid heat exposure. The negative effects on performance only seem to occur in the presence of hyperthermia, thus temperature *per se* does not imply necessarily a decrease in performance. This opens a window of opportunity related to voluntary heat exposures as a training method in cycling.

2. Heat training adaptations

Acute and prolonged heat exposure facilitates physiological responses and adaptations that favour the regulation of human temperature (Lundby et al., 2023). The reported improvements in performance in hot conditions after 10 days of acclimatization can reach 8 to 15% (Keiser et al., 2015). Also, there is a 4 to 6% increase in plasma volume and sweat rate, and there appears to be greater salt retention, which means less loss of electrolytes (Tyler et al., 2016).

At the cardiovascular level, some studies show that correct acclimatization allows increases in nitric oxide (blood pressure controller), a possible greater angiogenesis (creation of blood capillaries), an increase in the protein mTORc1, which consequently results in an increase in protein synthesis and likewise a possible increase in haemoglobin values (Wingo et al., 2012). In parallel, acclimatization may generate cardiac adaptations such as greater cardiac preload or a greater stroke volume. According to the theory derived from the study by Hawley et al. (2018), the increase in plasma volume will result in a temporary haematocrit reduction during heat training protocols. Rønnestad et al. (2021) evaluated haemoglobin changes in 21 elite cyclists produced after 5 weeks (1-hour training sessions performed 5 times per week) of heat exposure (38°C, 65% humidity). They observed an improvement in performance due to a 5% increase in haemoglobin mass and a positive trend in plasma volume and total blood volume with respect to the control group (same training protocol at 15.5°C). However, the red series volume hardly showed modifications after this exposure to heat. This contradicts the study by Oberholzer et al. (2019) where in addition to improvements in plasma volume, the group that trained in the heat improved to a greater extent their haemoglobin mass, translating into a tendency towards a greater increase in the red series.

Oberholzer et al. (2019) provided great insight regarding the possibility that these changes in blood values may result in an increase in performance. Consequently, an increase in plasma volume by 206 mL (intravenous infusion) resulted in an improvement of around 4% in VO_{2max}, and a significant increase in stroke volume. In addition to all the above, adequate heat acclimatization will allow blood flow to the skin to be reduced during lower intensity exercise due to greater thermoregulation. Regarding sweating, good acclimatization allows a decrease in heart rate during submaximal temperatures and an increase in thermal comfort. The increase in plasma volume seems to cause a decrease in the sweating threshold, as well as an increase in total sweating volume, avoiding an increase in core temperature that could reduce performance. Specifically, in the study carried out by Smith & Havenith (2019), they verified torso sweating at two different intensities (55% and 75% of VO_{2max}) before and after exposures to 6 consecutive days at 45°C for 90 minutes. The results showed an increase in gross sweating and sweating rates, this being a great indicator of acclimatization to heat. Additionally, the loss of electrolytes such as Na^+ through sweating seems to be reduced after correct acclimatization protocols (Buono et al., 2018).

Optimal acclimatization will also result in a reduction of the rate of perceived exertion. Pryor et al. (2019) examined the effectiveness of immersion in cold and hot water after training in temperate conditions (18°C). The sample was divided into two groups: the first carried out immersions in hot water and the second in warm water. They reported that the hot water group began to sweat earlier and had a lower body temperature and a lower feeling of perceived exertion in both types of tests (at 18 and 33 °C).

As the cyclist is exposed to heat, his sweating rate increases. The stabilization of this parameter could be used, accordingly, as a measure of proper heat acclimatization. At the start of the acclimatization process, sweating rate is still not optimal since the body will try to protect itself from the loss of plasma volume by lowering this thermoregulatory function. Likewise, the increase in plasma volume will cause the sweating rate to increase and help optimally evacuate heat. Hydration will be decisive, since its absence limits sweating rates and, consequently, performance. Given the same relative intensity, at the beginning of heat exposure heart rate will be higher, but as the subsequent exposures occur, heart rate will be reduced until stabilization. During the first exposures, to try to preserve cardiac output, heart rate will be increased due to the temporary loss of systolic volume. Finally, the body temperature at a certain intensity will also be higher until stabilization.

Training under heat conditions seems to result in physiological adaptations that may be useful not only during these specific conditions but also, according to several studies, in thermoneutral environments. The exposure to heat and humidity should be progressive and gradual and, ideally, should be monitored with specific markers such as the rate of perceived exertion, cardiac drift, core temperature and sweating rate.

3. Heat training protocols

There are different methods and combinations that allow cyclists to improve their performance in hot conditions. Racinais et al. (2015) studied the influence of different acclimatization periods on performance. Nine cyclists completed three 43.4km time trials at approximately 37°C with acclimatization periods of 1, 6 and 14 days. The data were compared with the average of this same test in cold conditions (approximately 8°C) performed before and after heat acclimatization. During this acclimatization period, cyclists spent a minimum of 4 hours a day in temperatures of 34°C, with a relative humidity of 18%, but they slept, rested and ate in air-conditioned facilities. They observed that, with one day of acclimatization, there was a marked decrease in the impairment in power production, which decreased further after 6 days of acclimatization and was almost completely reduced after 14 days. They also saw that heat acclimatization allowed the completion of the heat time trial in a similar time to the cold time trial.

Years later, heat acclimatization strategies in the road to the Qatar World Championship were also explored (Racinais et al., 2020). 61% of those surveyed did some type of heat exposure before the World Championship. Some cyclists only performed between 1 to 4 days of exposure but 38% of all cyclists underwent acclimatization periods of at least 5 days. These strategies depended on the level of the athletes, as most elite cyclists spent 7 days either training in high temperatures or living in a hot environment before arriving to Qatar, with far lower rates reported for junior and under-23 cyclists. Along these same lines, Lorenzo et al. (2010) analysed a group of cyclists who had to perform a stress test and a time trial in a cold (13°C) and warm (38°C) environments. The athletes were subsequently randomized to 10 days of light aerobic training at a temperature of 40°C or 13°C. After the completion of the training protocol, there was an increase in plasma volume, VO_{2max} and cardiac output in the group that had undergone acclimatization. In fact, the researchers observed that the group that had acclimated to the heat not only increased its plasma volume, but when performing the testing in hot environment they improved their performance by 5-8%. One of the most curious facts was not only the performance increase in hot environments, but also the increase in VO_{2max} (5%) and time trial performance (6%) when tested in cold temperatures.

These results have, however, been refuted by other researchers. For example, Nybo & Lundby (2016) showed that 2 weeks of training in the heat (35ºC) improved performance in a time trial carried out at that temperature by 16%, but they did not observe changes in VO_{2max}, peak power, or performance in a time trial conducted in cold temperatures (13°C). In fact, they concluded that heat acclimatization would be unable to increase performance in cold temperatures because the increases in plasma volume would be too small to bring improvements. Furthermore, an increase in plasma volume alone would not necessarily improve performance if it does not occur coincidentally with an improvement in the ability to transport oxygen (that is, if haemoglobin levels do not increase despite the increase in blood volume). In a study carried out by Racinais et al. (2019), 21 cyclists trained for 5 weeks at either 40°C or 15°C. In addition to the expected improvements in plasma volume, the results showed that the group that trained in the heat improved their haemoglobin mass to a greater extent, with a slight correlation with the increase in plasma volume. In this sense, the authors hypothesized that the increase in erythropoiesis could be a compensation mechanism for the increase in plasma volume to maintain stable haematocrit (since, if the number of red blood cells did not increase and only plasma volume increased, haematocrit would be decreased).

There's still no scientific consensus regarding the ideal number of exposures as it will depend on many factors such as exercise intensity or duration and/or environmental conditions. Furthermore, not all adaptations to the variables explained above can always be expected with the same number of exposures. According to Armstrong & Maresh (1991) and Rønnestad et al. (2021), variables such as heart rate adapt much earlier than others such as sweat rates. Longer exposures (>14 days) seem to produce greater and more lasting adaptations than shorter ones (<7 days) (Périard et al., 2016). Traditional protocols recommend that athletes train 60 to 90 minutes a day in elevated temperatures, for approximately 2 weeks, either traveling to a climate similar to that of the conditions of the event or using an environmental chamber that simulates the desired conditions (Racinais et al., 2015). Other authors such as Lundby et al. (2021), in more recent studies, have observed that 10 days of acclimatization, with daily training sessions at 35°C with thermal clothing combined with immersion in hot water, are also effective in improving performance in hot conditions in highly trained cyclists.

Finally, as to whether continuous or intermittent expositions are desirable, Karlsen et al. (2015) and Mikkelsen et al. (2019) showed similar advantages provided the number of exposures was equal. However, not more than 2 consecutive days without exposure are recommended, with a minimum effective dose of between 6 and 10 exposures. Regarding the intensity at which the exposures should be carried out, this may depend on the temperature since performing at high intensity with temperatures that are close to 38-40°C may be impossible to sustain. Based on research carried out by Schmit et al. (2018) training at low intensity in the heat seems to provide optimal results. Taking all of the above into account, longer durations and intensities approaching 50-60% of VO_{2max} would be more desirable compared to shorter exposure times with higher intensities.

One of the key factors of heat training protocols are the de and re-acclimatization timings. The rate of deterioration of adaptations will vary considerably depending on many variables such as duration, type of acclimatization or training status before heat exposure. Previous evidence shows that each day without heat exposure results in a deterioration of around 2.5% in variables such as heart rate. As of now, there is little research on this topic, and it could only be speculated that, given the timing of acclimatization, the loss of adaptations could occur during a similar timeframe of 2-4 weeks (Flouris et al., 2014; Wingfield et al., 2016).

The evidence highlighted in the previous paragraphs points towards strategies that should be centred around long exposures (2-3 weeks) of several hours per day while training at low intensities and performed in the weeks prior to the key event as loss of adaptations should be expected. Current evidence regarding the possibility of transferring these adaptations into thermoneutral environments is still conflicting.

4. Conclusions

The impact of heat and humidity on cycling performance has been discussed in the scientific literature for several decades. However, research performed in this century and specifically in the last decade has shown that training with heat exposure has potential to ameliorate performance during these extreme conditions. There is conflicting evidence regarding the real utility of these interventions when attempting to improve performance in other environmental situations. The expected changes after voluntary heat training are related mainly to central adaptations such as increases in VO_{2max}, plasma volume and haemoglobin levels. Heat training should be performed in the 10 to 21 days prior to the key event, with daily exposures integrated in the training sessions and performed at low intensities (50-60% VO_{2max}. Adaptations should be monitored with the rate of perceived exertion, body temperature, sweat rates and cardiac drift, among others. Detraining from heat should be expected when subsequent exposures are not implemented, and thus consecutive exposures before key events should be correctly timed.

Conflicts of Interest: The authors declare no conflict of interest.

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