Kudusmart White Paper
The Importance of Monitoring Thermoregulatory Efficiency in Athletes

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Synopsis

- High performance within sports requires effective thermoregulation with maintenance of core temperature within a narrow range.
- On land, in normal conditions, the main mechanism by which athletes can lose heat is through the evaporation of sweat (produced by eccrine glands).
- Eccrine sweat glands are trainable through usage.
- Training thermoregulation invokes additional advantages including increased blood volume, improved retention of electrolytes and may contribute to the development of the sports adrenal medulla.
- Measuring and monitoring sweat rate is a simple but key step to tracking and assessing thermoregulation.

Introduction

Human physiology is dependent on maintenance of a stable core body temperature (homeostasis) within a relatively tight range of 37°C ± 2.0°C . A core body temperature outside this range will lead to a deterioration in performance, and greater deviations (hypo- and hyper-thermia) can lead to serious medical issues or death. The focus of this white paper is the effect of physical activity on core body temperature and the prevention of hyperthermia

The process of converting chemical energy (e.g. carbohydrates and fats) to mechanical power is inefficient with almost 80% of the available energy being lost as heat. As individuals train, improving their power generation, oxygen uptake and circulatory capacity, their thermal load will also increase. This greater heat loads requires an equal increase in cooling capacity. Additional cooling capacity is also required to cope with increases in environmental temperature or higher humidity.

The primary mechanism for cooling, in exercising humans on land, is the evaporation of sweat. When activated by the autonomic nervous system, sweat glands transport salt and water out of the interstitial space around them into the lumen of the secretory coil of the gland. That water is, initially, relatively salty. As this salty fluid flows up through the dermal duct of the sweat gland sodium and chloride is reabsorbed and the fluid becomes less salty. It leaves the gland from the upper coiled duct onto the skin, cooling the body as it evaporates (Sonner et al., 2015). Like other structures within the body such as muscles, the lungs or heart, sweat glands may be trained and are subject to both hypertrophy and atrophy.

In addition to the improved cooling capacity induced by thermoregulatory training, there are additional benefits with respect to the increased retention of key electrolytes.

The training and detraining response of sweat glands is relatively rapid (with significant improvements detectable within 14 days and with maximal training taking longer). However, while the importance of sweating and thermoregulation is understood by medical practitioners it receives remarkably little attention in training plans. This is most likely due to the historical lack of a simple and cost-effective means to measure or assess the thermoregulatory performance of individuals.

The impact of increased core body temperature on athletic performance

A rise of core body temperature above about 39°C has a number of detrimental effects:

- Earlier onset of fatigue
- Reduced motivation
- Compromised cognition and concentration

At the upper extreme elevated core body temperature may lead to heatstroke or eventually death.

It should be noted, however, that the optimal muscle temperature is somewhat higher than that for core body temperature, at around 38.5°C to 39.5°C .

It is also notable that highly trained individuals will not only exhibit greater ability to lose heat, they may also be able to sustain a higher core body temperature.

Thermoregulatory efficiency is critical for endurance activities, even if the thermoregulatory capacity is not limiting in terms of immediate short-term heat load. In short duration events the thermal capacity of the body, simply by virtue of its mass, will limit the rise in core temperature. Indeed, in sprint events such as athletics track disciplines (<1500m) and cycling velodrome disciplines, it may be desirable to increase environmental temperature to facilitate higher muscle temperatures, and lower wind resistance, thereby improving performance.

Nevertheless, the definition of "endurance events" is far broader than might be expected, and can include a wide variety of "open" (interference) sports such as football, cricket, rugby, tennis etc. These sports involve extended bouts of intermittent burst activity, where there is often insufficient time between bursts to achieve a reduction in core body temperature. Over the duration of play there will be a steady increase in core body temperature similar to that seen in "closed" athletic activities such as endurance running (figure 1) and road cycling.

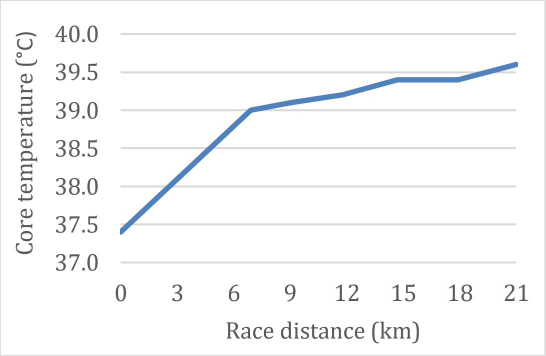

Figure 1 – Mean core temperature for a group of athletes competing in a half-marathon. Data taken from Lee et al, 2010.

Early onset fatigue

The most obvious effect of raised core body temperature is that of time to fatigue. (MacDougall et al, 1974; Walters et al., 2000).

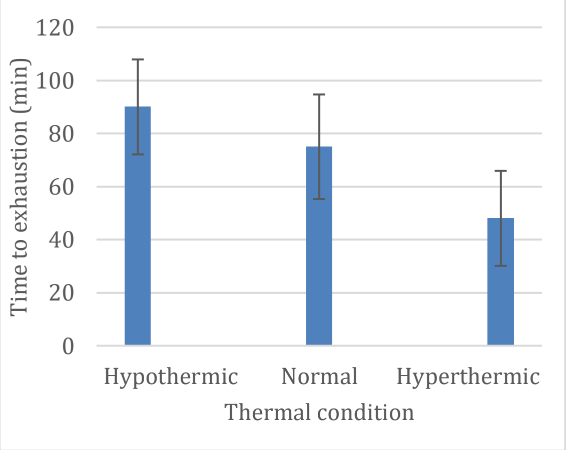

Figure 2 – Time to exhaustion of athletes in hypothermic, normothermic and hyperthermic conditions. Data taken from MacDougall et al, 1974.

MacDougall et al (1974) had participants exercise under cold (hypothermic), normal or hot (hyperthermic) conditions (figure 2). Time to exhaustion is critically dependent on temperature. Fatigue, in a physiological context, describes a decline in output as a result of sustained activation. In more general terms it is often used to describe the feeling of tiredness which leads to a decline in performance. In endurance sports there are several well know causes of fatigue with a run-down in energy stores or a rise in core temperature being the most common.

Motivation

Psychological and physiological mechanisms interact during physical performance with each having the potential to alter the other. It is well known that when humans are put under stress they are capable of greater physiological performance – every athlete who has raced will be aware of that. Equally, when our central nervous system perceives danger it will throttle-back our physiological capability whether it is as simple as slowing for a tight corner or descending cautiously down a steep hill. Noakes advocates similar psychological influence but with regard to internal physiological parameters which an athlete cannot easily perceive but may be detected by internal sensors (Central Governor Theory) Noakes, T. D., St Clair Gibson, A., and Lambert, E. V. (2005). The rise of core temperature and the subsequent impact on other physiological systems may be similarly sensed and used to alter performance.

Whether it is a protective feedforward mechanism or a direct splitting of circulatory output to support thermoregulation it is clear that increased core body temperature will lead to early termination of exercise. Race times clearly show the negative impact of hot and humid conditions (Ely et al., 2007).

Cognition

Not only does elevated core temperature affect athletes' motivation it also has an impact on cognition and mental acuity. This is of particular relevance in open sports where competitive tactics and match awareness can have a major impact on results. As shown by Sunderland and Nevill (2005) the skill of field hockey players reduces when they are performing in the heat.

Heat balance in the exercising human

Heat balance, rather obviously, requires that the heat loss to the external environment matches internal heat generation. The heat exchange with the external environment is the combination of evaporation (sweat and ventilation), radiation and conduction. Internal heat generation, in exercise, is dominated by the metabolic consequences of servicing mechanical work.

Since only around 20% of the energy liberated by metabolism appears in the form of external work, internal heat generation can be very large indeed (in excess of 1kW).

Heat loss from convection, conduction and radiation are typically low – at least on land in normal conditions. They depend on skin blood flow as well as the local environmental conditions (temperature, humidity, altitude, wind speed, clothing, etc).

It is often thought that an exercising athlete can lose substantial amounts of heat via radiation. However, radiative losses are highly dependent on environmental and skin temperature such that during race efforts, under normal conditions, radiative losses account for a small amount of the overall heat loss recorded. In the event that environmental temperature increases above skin temperature then the athlete will experience radiative heat gain.

Evaporative heat loss results from both sweating and ventilation. Most mammals rely on respiration (panting) as their primary means of cooling during exercise. The dominant means of cooling for humans is sweating and some scientists believe that this was a major evolutionary change that allowed humans to thrive as persistence hunters of animals such as the kudu.

Sweating to thermoregulate

Humans have over 2 million thermoregulatory, eccrine, sweat glands. We also have other sweat glands, apocrine glands, that are activated by stress. However, these play little role in thermoregulation. The eccrine sweat gland has a duct that when activated causes salty water to flow out of the interstitial space and into the duct. As this water passes along the duct much of the salt is reabsorbed. The bigger and better trained a sweat gland the more of this salt it will reabsorb.

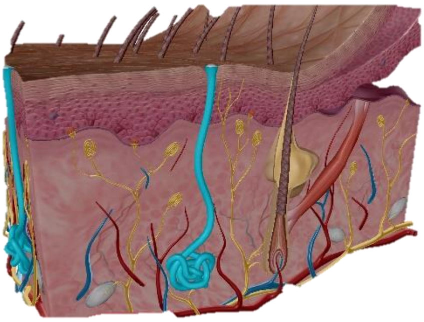

Figure 3 – Cross-section sketch of skin showing an eccrine sweat gland (blue) and other structures. The human eccrine sweat gland has three regions; the deepest section is the secretory coil. The middle section is the dermal duct. The upper coiled duct is where the diameter expands slightly and the sweat is released onto the skin (Sonner et al., 2015)

Sweat glands are trainable in the same way that other organs can be trained by usage. This forms a key component of the thermal acclimation process. While many athletes are familiar with the adoption of thermal acclimation prior to competitive events in warmer/more humid environments there is evidence that it is beneficial for performance under normal conditions (Lorenzo et al., 2010). It is therefore desirable to add thermal adaptation to regular training regardless of the likely environmental conditions on competition day.

Adding a thermoregulatory training component will:

1. Increase maximum cooling capacity.
2. Improve electrolyte retention and therefore allow greater levels of relative dehydration without a performance penalty.
3. Improve the ability to support higher core body temperature.
4. Increase plasma volume and therefore improve aerobic ability and resistance to dehydration.

Sweat rate measurement

Until now there has been no means to regularly and easily monitor an individual's thermoregulatory (sweating) efficiency. There are a number of technical complexities which make the process non-trivial.

There are existing methods which are suited to the university research or sports science laboratory including:

1. Nude body weight measurement before and after exercise, with adjustments for ingestion and excretion.
2. Technical absorbance patches that stick to the skin and absorb the sweat during an exercise session.
3. A ventilated capsule machine that the athlete is tethered to and analyses sweat losses, often on the arm.

KuduSmart is a new method for measuring sweat rate. It is a wearable device, linking to an Android app that provides a real-time view of sweat rate. The benefits and drawbacks of each method are highlighted below:

Method	Benefits	Drawbacks
Ventilated capsule	Gold standard of accuracy. A live data feed can be provided.	Expensive equipment that requires a lab, and lab skills to operate. The equipment is large and must be static.
Technical absorbance	High accuracy levels. Relatively low cost.	Requires lab skills and high precision scales. Only measures total sweat loss over the duration of the test.
Athlete weighing	Very low cost. Relatively easy to perform the test. Does not require a lab or lab skills.	Low accuracy level, unless a very accurate scale is used, and a reliable protocol is followed. Only total sweat loss over the duration of the test.
KuduSmart	No lab, or lab skills required to operate the equipment. Real-time sweat rate.	The current device only measures local sweat rate.

Implications of measuring thermoregulation

Physiology is complex. No single physiological measure captures all that is required to track and optimize an athlete's progress.

Currently many elite-level athletes track a range of metrics including:

- Distance run,
- Speed,
- Gait related data,
- Performance times,
- Peak power,
- VO2max, or proxies,
- Lactate threshold,
- Haematocrit,
- Number of special sessions,
- Heart rate (both exercising and resting)
- Heart rate variability,
- Hours and quality of sleep,
- Subjective measures of well-being,
- Weight,
- Food intake,
- Skin-fold fat measurement,

Coaches use these data to improve athlete performance in the knowledge that there is a complexity which requires knowledge of interacting variables.

To take an obvious example, knowledge of a runner's heart rate during training is almost meaningless. However, when the pace is known then elements of aerobic fitness can be tracked and predicted. Without the heart rate data submaximal efforts become simply training sessions rather than opportunities to assess training effectiveness.

Without measuring the biological system it remains an unknown element which may, or may not impact on peak performance. Measuring the capability of the thermoregulatory system provides a simple insight into an athlete's largest organ – their skin. With knowledge of its performance the first question can be addressed – does the training plan need adjustment? Furthermore, as adjustments are made, are they effective; are changes in competition tactics required: and, can team selection benefit from better knowledge of each athlete's thermoregulatory fitness?

Training plans can be improved through the assessment of thermoregulatory capacity by identifying athletes for whom this is a limiting system and codifying how much thermal training is needed. The short-term acclimation process before a particularly hot event can be refined with the knowledge of how much thermal training is enough to produce the required adaptation. In addition, and more critically, it is possible to assess how quickly that adaptation is lost during any taper/pre-competition rest period. Effective tapering, without loss of thermal adaptations is currently very poorly understood.

Coaches may use this data in their tactical decisions for competitive events, such as pacing. For instance, runners and cyclists who are very well adapted to heat, with large sweat glands capable of retaining most of the sodium in sweat, may benefit from the weight loss caused by sweating during the event. As the race or match progresses they gain a power-to-weight ratio benefit in comparison to athletes using a greater rehydration strategy. Knowledge that your athlete is not as well adapted to heat as others may suggest a need to focus on gaining a lead early on in a competitive event.

Professional teams may also use data on thermoregulatory performance to better select athletes for a specific event. For example a Premier League football club that is competing in the European Champions League may have a match in the heat of Spain, followed by one in northern England, with only a few days between. Knowing which players will perform well in the heat and which are is better adapted to the cooler, UK game, is valuable knowledge that may influence team selection.

Professional sports teams and National Governing Bodies often use physiological measures to identify talent in young athletes. Currently, aspiring athletes are not judged on their thermoregulatory ability, despite this being of significant importance to a range of sports. Employing thermoregulatory monitoring as part of the talent identification process provides another dimension to the athlete assessment.

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