

3.1 Effect of heat on performance

Sometimes football is played in extreme environmental conditions (either cold or hot). It is well known that endurance performance is reduced in hot conditions, but short (sprint) disciplines may actually benefit from them. In football, a single sprint may not be affected, but fatigue will develop more rapidly, and the number of high intensity sprints will decrease. In this section we will discuss the effects of heat on endurance performance, the reasons why it is impaired and strategies to minimise the impact of heat on performance.

Human body temperature is regulated within narrow limits. A normal temperature is 37°C. During exercise, body temperature may rise to 39.5°C, but normally 40°C is hardly ever reached or exceeded. The lowest temperature is around 36°C, so the normal range is 36–39.5°C. To keep core temperature within such a narrow range, a complex thermoregulatory system makes sure that heat is dissipated to prevent overheating and that body heat is conserved to prevent undercooling. In the next section we will discuss mechanisms of heat gain and heat loss and its central regulation through the hypothalamus.

3.1.1 Thermoregulation

During exercise in hot environmental conditions, there are a number of ways in which a player gains heat and a player has a number of mechanisms to dissipate heat (Wendt, van Loon, & Lichtenbelt, 2007). Conversely, in cold conditions the body has mechanisms to minimise heat loss. This makes it possible to prevent core temperature from rising or dropping to dangerous levels. Heat can be gained from the environment and from muscle contraction. Environmental heat stress is determined by the ambient temperature, relative humidity, wind velocity, and solar radiation (both directly from the sun and reflected from the ground). During exercise, the working muscles produce heat at a high rate and this is a major cause of the rise in body temperature.

Let's do a quick calculation of the potential impact of this heat production. In the following example, we will do the calculations for a 75-kg football player with a VO_2max of 4.3 L/min and 15% body fat. Football is played with an average intensity of 70% VO_2max and, thus, this player would play with an average VO_2 of 3 L/min. Energy expenditure is roughly 5 kcal per litre of oxygen consumed per minute. Approximately 20% of this is used for muscle contraction; the remaining 80% is heat. So, heat production is 12 kcal/min or 720kcal/hour (or 837 Watt). The specific heat capacity for lean tissue is 0.83 kcal/kg/°C and for fat this is 0.41 kcal/kg/°C. So, for our player with 15% body fat, this means that the specific heat capacity of the body is $(0.85 \times 0.83) + (0.15 \times 0.41) = 0.77$ kcal/kg/°C. Heat storage would therefore be $75 \text{ kg} \times 0.77 \text{ kcal/kg/°C} = 57.5 \text{ kcal/min/°C}$.

This means that with 720 kcal of heat production would take 12.5 min to increase body temperature 1°C and it would take approximately 37 min to reach dangerous levels. During high intensity physical activity, heat production through supramaximal

efforts will be many times higher and core temperature could reach critical levels within 10-12 min.

Mechanisms to dissipate heat are therefore crucial. If the skin is hotter than the surroundings, heat is lost through the skin by physical transfer (evaporation of sweat, convection, and conduction) to the environment. If the environment is hotter than the skin, heat is gained by convection (convection is the exchange of heat between a solid medium (e.g., the human body) and one that moves (e.g., air or water) and conduction (direct transmission of heat to environment, without movement). Conduction is usually only a small percentage of heat loss (3%). Radiation (the transfer of energy waves by emission from one object and absorption by another) also plays a role. All objects that are not absolutely zero temperature radiate heat. Our body radiates heat, the sun radiates heat. Radiation in thermoneutral conditions accounts for approximately 60% of total heat loss. When the environmental temperature is high and radiation heat from the sun is high, radiation from the body is insignificant and heat is gained. More radiation heat is gained when there is no cloud cover or shade.

Evaporative heat loss is the final methods to dissipate heat. A small fraction of this occurs through ventilation and diffusion for which we do not have control mechanisms. Far more significant is evaporative cooling through sweating. In dry air, significant amounts of sweat can evaporate. Evaporation of 1 L of water from the skin will remove 573 kcal of heat from the body. However, if the environment is saturated with water vapour (i.e., relative humidity = 100%), evaporation of sweat does not occur, and the body does not lose heat. Relative humidity is therefore an important factor, because high humidity severely compromises the evaporative loss of sweat and sweat must evaporate from the body surface to exert a cooling effect. (Jeukendrup and Gleeson, 2018. <https://bit.ly/2LC9XB7>) When sweat rolls off the skin, it has virtually no cooling effect.

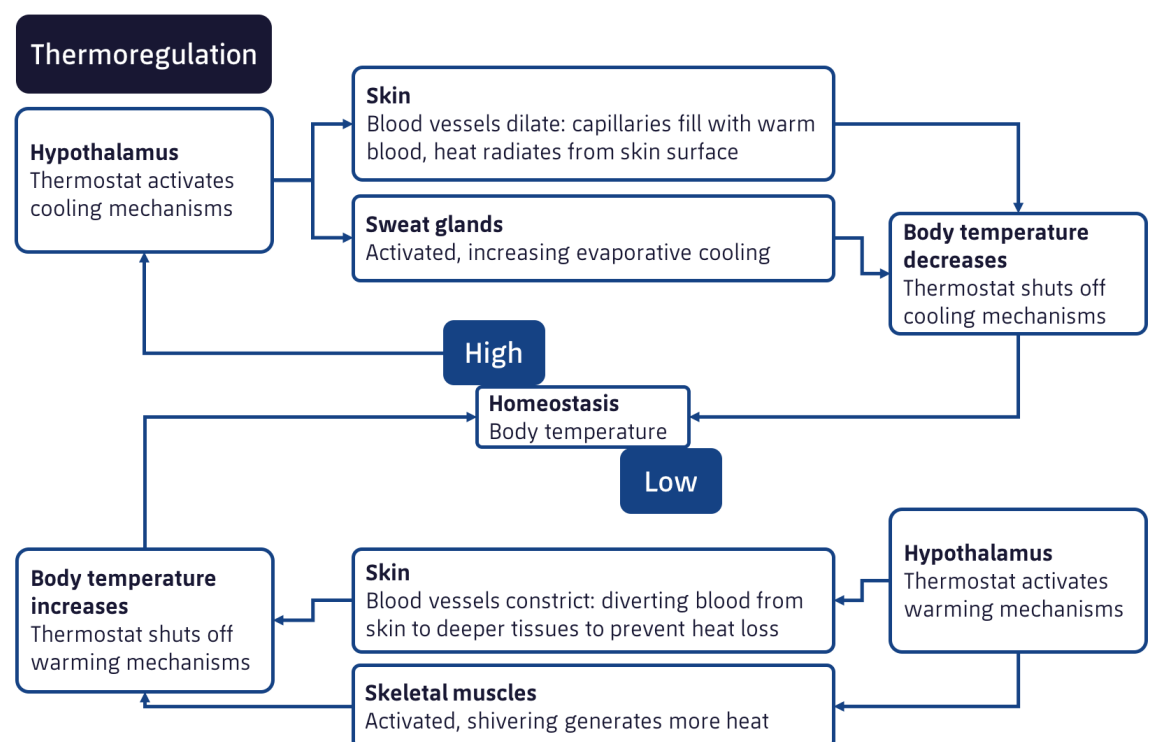
The rate of heat transferred away from the body core is the product of the skin blood flow and the temperature difference between the core and the skin. A first response is, therefore, an increase in cutaneous vasodilation. Adjustments in the cutaneous vascular tone will modulate skin blood flow. Blood flow is not only regulated by thermoregulatory responses, but also by non-thermoregulatory responses. For example, muscle contraction will increase the demand for blood flow and might result in vasoconstriction. When exercising in hot conditions, the cutaneous circulation is subject to conflicting demands: vasoconstriction to allow more blood flow to the muscle and vasodilation for cooling purposes (Kellogg, Johnson, & Kosiba, 1991).

High skin blood flow alone may not be sufficient to remove heat from the body core during exercise in hot, humid conditions when the skin temperature rises because of the inability to evaporate sweat. The effectiveness of this route of heat loss also depends largely on the amount of body surface available for heat exchange and the temperature gradient between the body surface and the surrounding atmosphere. Inappropriate clothing makes it more difficult to dissipate heat. When ambient temperature is close to body

temperature, heat loss via increased skin blood flow is minimal. The body then depends almost entirely on evaporative cooling (sweating) (Jeukendrup and Gleeson, 2018. <https://bit.ly/2uP4487>)

The hypothalamus is the central thermostat that acts like a normal thermostat making sure the temperature in the body stays within relative narrow limits (Figure 1). The hypothalamus has many heat- and cold-sensitive neurons in its pre-optic and anterior nuclei. In addition to sensing the core temperature, the hypothalamus also receives afferent information from thermoreceptors throughout the body, including the spinal cord, abdominal viscera, greater veins and the skin. When body temperature increases, this is sensed by the hypothalamus itself as well as by these peripheral thermoreceptors and, thus, the hypothalamus will activate cooling mechanisms. These include vasodilation of capillaries in the skin. The skin will fill with warm blood from the core and heat can radiate to the environment. Simultaneously, sweat glands are activated for evaporative cooling (Figure 1). The result is that body temperature will decrease, and this means the thermostat can shut off again.

Figure 1: Regulation of body temperature and the role of the hypothalamus



Source: Jeukendrup. www.mysportscience.com

When temperatures are low, this is sensed as well, and the hypothalamus will activate warming mechanisms: blood vessels in the skin constrict so less heat is lost and skeletal muscles are activated. Muscle contractions, especially shivering, increase heat production. When the body heats up, the hypothalamus shuts off the warming mechanisms.

5.1.2 Effect of heat stress on performance

It is difficult to measure football performance in competition and compare different environmental conditions, but there are a lot of data from endurance sports. For example, when marathon times were studied in different WBG temperatures for a given marathon time, the findings were that there is a performance decrement with increasing heat stress. Faster runners are affected less by the heat than the slower runners, but in all cases, performance is affected by temperature. The fastest marathon times are usually seen around temperatures of 10-11°C. The optimal temperature for football is not known because endurance may be impaired in the heat, but sprint performance may be improved. It is likely that it will be at a higher temperature than marathon running, but not too hot, as endurance may be compromised too much. Grantham et al. (2010) suggested that players who play at an air temperature below 22 °C are not at risk of heat stress and its negative consequences, while the risk is low between 22 and 28 °C and high above 28 °C. Football matches played at 43 °C demonstrated a decline in total game distance by 7% and in high intensity running (>14 km/h) by 26% in hot conditions when compared to control conditions (Mohr, Nybo, Grantham, & Racinais, 2012). However, peak sprint speed was 4% higher in hot conditions, while there were no differences in the quantity or length of sprints (>24 km/h). Passes and crosses success rates were 8 and 9% higher in hot conditions compared to control conditions (Mohr et al., 2012). Playing in hot conditions resulted in a dramatic increase of peak core (T_{c} : $39.5 \pm 0.1^{\circ}\text{C}$) and muscle (T_{mu} : $40.3 \pm 0.1^{\circ}\text{C}$) temperatures (Mohr et al., 2012).

One study suggested that, in football, high intensity running may not be affected by heat actually, but rather, the pacing may change, and recovery times may increase (Coker, Wells, & Gepner, 2018).

However, an analysis of the World Cup in Brazil in 2014 in mixed conditions, some extremely hot, suggests that top-level players seem to modulate their activity pattern during matches in a hot and humid environment (i.e., less high-intensity but more low-intensity running and successful passes) to preserve the global match characteristics (i.e., similar total distance covered, similar actual playing time, peak running speed and goals scored). (Racinais, S., Alonso, J. M., Coutts, A. J., Flouris, A. D., Girard, O., Gonzalez-Alonso, J., Hausswirth, C., Jay, O., Lee, J. K., Mitchell, N., Nassis, G. P., Nybo, L., Pluim, B. M., Roelands, B., Sawka, M. N., Wingo, J. E., Periard, J. D. 2015. <https://bit.ly/2ETri87>)

For a long time, there was a theory that there was a critical temperature: once this temperature was reached, fatigue would occur in an attempt to prevent damage as a result of a continued rise in core temperature. This theory was derived from a number of studies in which fatigue coincided with core temperatures around 40 °C. It is striking that, with heat acclimation, subjects have a different starting core temperature, but exhaustion occurs always at the same temperature. An acclimation study conducted during 10 days of heat acclimation demonstrated that, even though every day exercise to exhaustion increased, the temperature at which exhaustion occurred stayed the same. This means that the rate of heat accumulation was lower every day.

Other studies have shown that pre-cooling the body can delay exhaustion, while pre-heating it will accelerate it. If the exercise is initiated with a lower starting temperature, it will take longer before exhaustion occurs and if initiated with higher temperature, it will take shorter. But the core temperature at the end was always the

same (around 40°C). Therefore, it is not surprising that it was concluded that there was a critical core temperature.

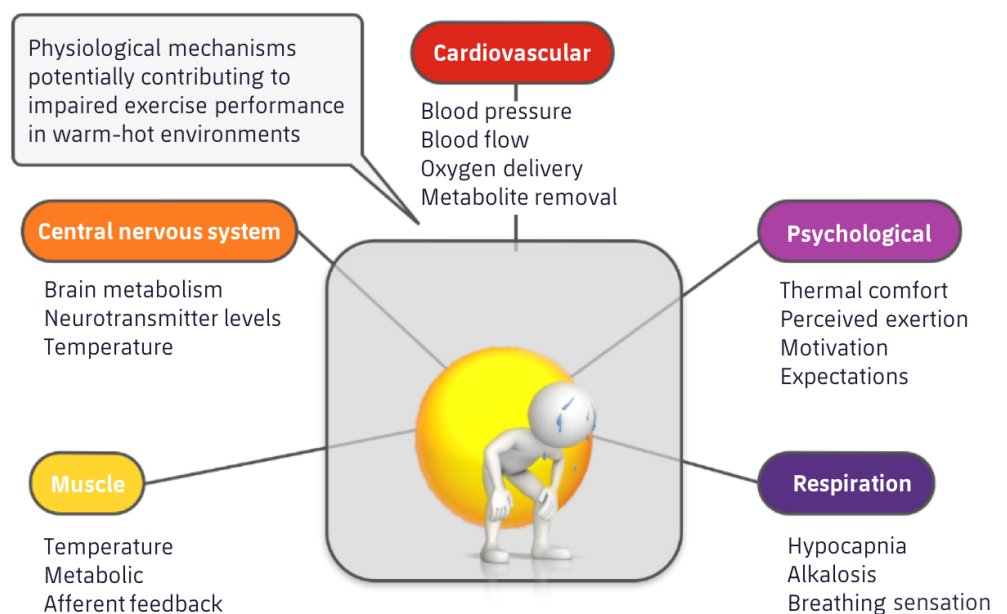
A single cause of fatigue in the heat may be a little too simplistic though; it is likely to be multifactorial (Nybo, Rasmussen, & Sawka, 2014). For instance, concomitant development of dehydration, which aggravates physiologic strain, seems to lower the tolerable core temperature at the end of exhaustive exercise in the heat. Enhancing the synaptic dopamine levels (using dopamine reuptake inhibitors) increases subjects' exercise capacity in the heat and results in higher core temperatures at the end of exercise without reported side effects. Finally, trained subjects seem to tolerate higher core temperatures better than untrained individuals and, thus, the concept of one critical core temperature as a sole explanation seems too simplistic.

Field and laboratory studies have clearly demonstrated that aerobic exercise is impaired in the heat and it is very likely that the causes of this are multifactorial.

Physiological mechanisms potentially contributing to impaired exercise performance in warm-hot environments are depicted in figure 2. Hypo-hydration may exacerbate these effects. If hypo-hydration is sufficiently severe, all physiological functions are likely to be compromised, though the effects are more selective at the levels of hypo-hydration normally encountered.

Figure 2: Physiological mechanisms potentially contributing to fatigue during exercise in warm/hot environments

Impaired exercise performance in warm-hot environments

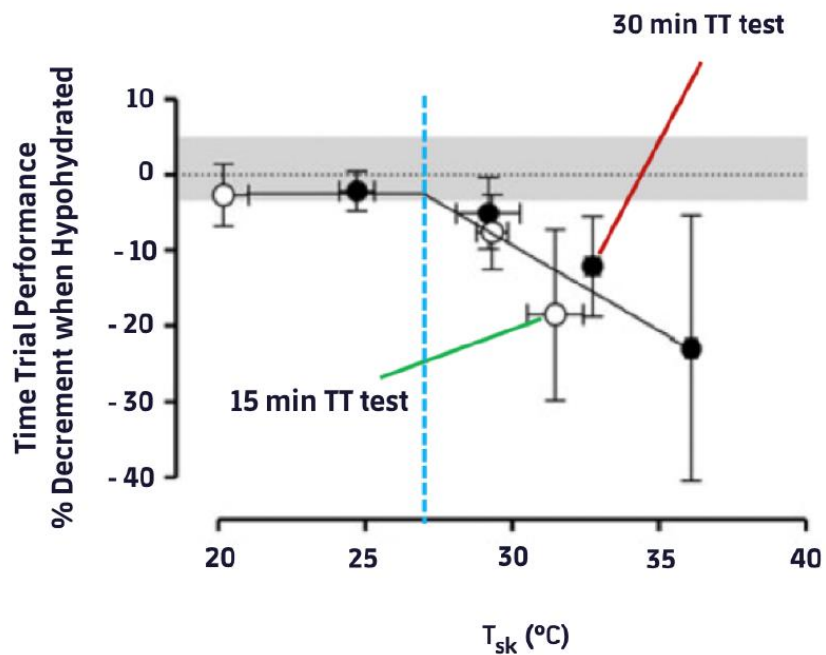


Nybo et al Comp Physiol 4: 657-689, 2014

Source: Nybo et al., 2014, <https://goo.gl/ae4Zrd>

Cheuvront, Kenefick, Montain, and Sawka (2010) proposed that impaired submaximal aerobic performance in the heat might be explained by warm-hot skin temperature reducing $\dot{V}O_{2\max}$. Figure 3, which contains data from a series of studies where performance was measured either through 15 or 30 minutes TT tests, shows that above skin temperatures of 27 degrees, performance starts to decline and for every 1°C rise in skin temperature, performance may decrease 1.3%. So, although core temperature is an important determinant of fatigue, skin temperature seems to play an important role too.

Figure 3: Time trial performance and temperature



Source: Cheuvront et al., 2010, <https://bit.ly/2RtjmAg>.

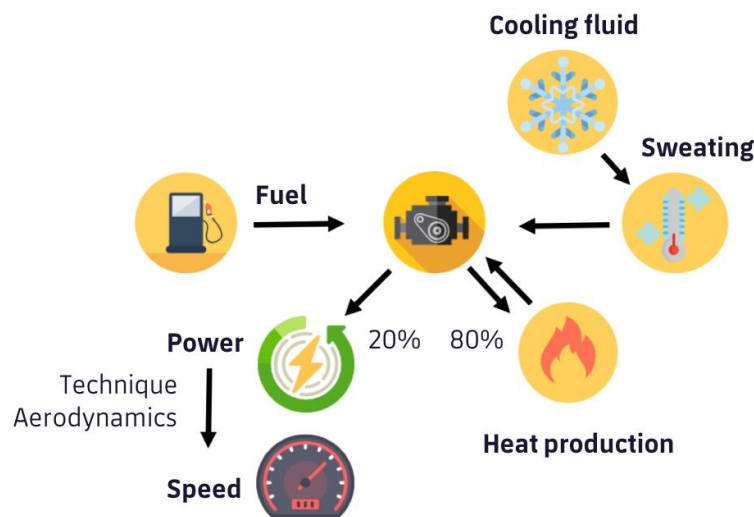
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3.1.3 Sweating

Our most important mechanism to dissipate heat in hot conditions is sweating. Let's use the analogy of an engine of a car (Figure 4).

Figure 4: Heat production and cooling. An analogy with a car

"The engine"



Source: Jeukendrup, 2018. www.mysportscience.com

A car's engine produces heat. For every unit of energy generated for movement, 4 units of energy in the form of heat are produced (20% efficiency). For every litre of oxygen consumed during exercise such as cycling or running, approximately 16 kJ (4 kcal) of heat are produced and only about 4 kJ (1 kcal) are used to perform mechanical work. For an athlete consuming oxygen at a rate of 4 L/min during exercise, the rate of heat production in the body is about 917 kcal/h. Especially in a hot environment, only a small proportion of the heat produced in active skeletal muscle is lost from the overlying skin. Rather, most of the heat is passed to the body core by the convective flow of venous blood returning to the heart. It has been shown that the rate of temperature increase in the belly of the quadriceps muscle group is close to 1 °C/min during the initial moments of high-intensity cycling. This rate of heat storage cannot persist, because the muscle contractile proteins and enzymes would be inactivated, and heat-induced denaturation would result within 10 minutes. Thus, most of the heat generated in the muscle is transferred to the body core. (Jeukendrup and Gleeson, 2018. <https://bit.ly/2LC9XB7>).

Like a car has a cooling system the body has several cooling systems with sweating being the most important one when it is hot. Blood flow from the core to the skin will transport warm blood and evaporation of sweat will cool down the skin and the

blood within it. When the blood volume decreases and skin blood flow becomes impaired, this has the same effect as running low on cooling fluid in a car.

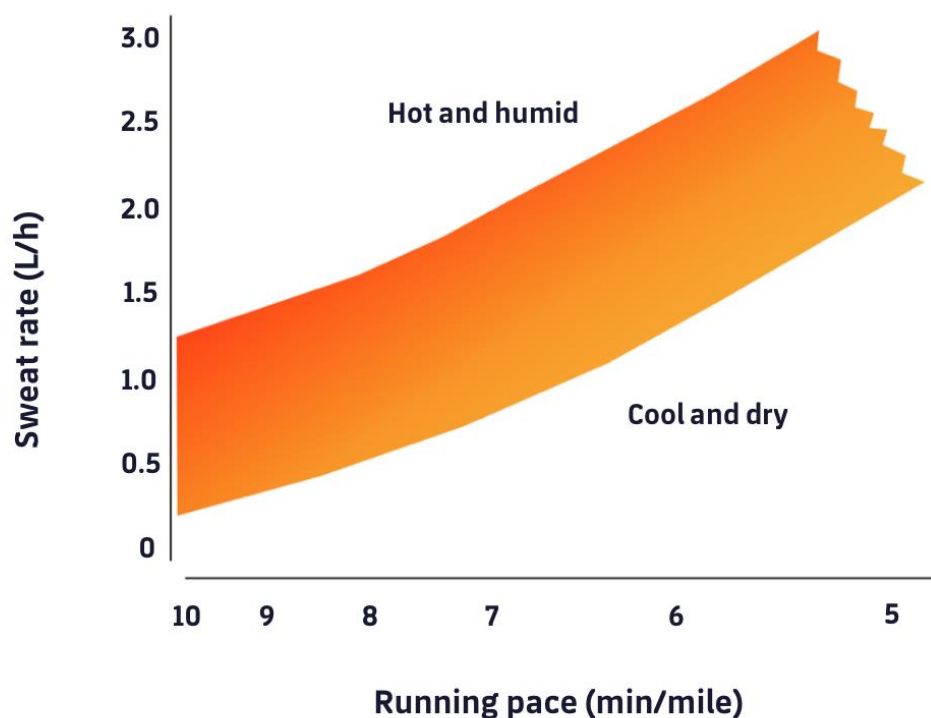
Humans have 2-4 million sweat glands, but there may be large individual differences in the number of glands and the way they are activated. This may be the explanation why some people sweat more than others. Activation of eccrine sweat glands causes sweat to be secreted onto the skin surface, thereby promoting heat loss as the water content of sweat evaporates. These glands can be found all over the body with higher densities in some areas than others. The glands are innervated by sympathetic nerves. Neural stimulation of the sweat glands elicits the secretion of sweat, which resembles blood plasma but without the proteins. Sweat, therefore, contains also some electrolytes with sodium being the most abundant one.

Sweat is hypotonic compared to plasma and this limits the losses of sodium and other electrolytes. The electrolyte concentration in sweat will decrease further with training and acclimation.

Sweat rates are typically between 0.5 and 2 L/h but can be as high as 3 L/h in extreme cases. In figure 5 you can see how sweat rate goes up with running pace and how cool and dry or hot and humid conditions affect it. For example, running at a certain pace would mean a sweat rate below 1 L/h in cool dry conditions and over 1.5 L/h on hot and humid conditions. During intermittent exercise with breaks, it is the average intensity that is important, taking into account the rest periods.

Figure 5: Sweat rate: a function of running pace (intensity) and environmental conditions

Sweat rate



Source: Jeukendrup. www.mysportscience.com

It is clear that a number of factors will determine sweat losses; these include:

1. exercise intensity
2. the duration of exercise
3. the number of sweat glands
4. acclimation
5. weather conditions
6. clothing

Having information about all these factors can help to predict sweat losses in athletes. How sweat losses can be predicted will be discussed in one of the following sections.

3.1.4 Dehydration and the effects on thermoregulation

When sweating becomes the primary way to dissipate heat, sweat loss must be matched by fluid intake to avoid dehydration. Although small levels of dehydration might be acceptable, larger losses may affect physiological function. As the body becomes progressively dehydrated, blood volume will decrease and this will affect both skin blood flow as well as sweat production. This in turn will result in a reduction in skin blood flow and, thus, sweat rate. This may then result in a rise or more rapid rise in core temperature, resulting in fatigue and possible heat injury to body tissues.

Dehydration also reduces the core temperature that a person could tolerate, because core temperature at exhaustion is generally about 0.4 °C (0.7 °F) lower in the dehydrated state. The main reasons why dehydration has an adverse effect on exercise performance include:

- reduction in blood volume
- decreased skin blood flow
- decreased sweat rate
- decreased heat dissipation
- increased core temperature
- increased rate of muscle glycogen use

Reduced maximal cardiac output is the most likely physiological mechanism whereby dehydration decreases a person's running capacity. Dehydration causes a fall in plasma volume, and a decreased blood volume increases the viscosity of the blood (thickness), lowers central venous pressure, and reduces venous return of blood to the heart. During maximal exercise, these changes can decrease the filling of the heart during diastole (the phase of the cardiac cycle when the heart is relaxed and is filling with blood before the next contraction), hence reducing stroke volume and cardiac output. During exercise in a hot environment, vasodilation of the skin reduces the proportion of the cardiac output available to the working muscles.

The larger rise in core temperature during exercise in the dehydrated state is associated with an exaggerated catecholamine response. This, in turn, may lead to increased rates of glycogen breakdown in the exercising muscle, which can contribute to earlier onset of fatigue in prolonged exercise.

Hypohydration also appears to attenuate strength, power, and high-intensity endurance by approximately 2%, 3%, and 10%, respectively,

suggesting that alterations in total body water affect some aspect of force generation. Although the mechanisms are not well understood, the physiological demands of strength, power, and high-intensity endurance suggest alterations in cardiovascular, metabolic, or buffering function are responsible for the performance impairment associated with hypohydration (Jeukendrup & Gleeson, 2018). It has also been suggested that hypohydration might directly affect some component of the neuromuscular system, but this has not been investigated yet. (Jeukendrup and Gleeson, 2018. <https://bit.ly/2LC9XB7>).

Besides the effects of dehydration on the cardiovascular system and muscles, dehydration is also associated with a reduced gastric emptying rate of ingested fluids during exercise in the heat. For example, one study reported a 20- 25% reduction in gastric emptying when subjects were dehydrated by 5% of body mass (Neufer, Young, & Sawka, 1989). A reduced gastric emptying will affect the delivery of carbohydrate and fluid during match or training and is likely to cause more gastro-intestinal discomfort.

Dehydration poses a serious health risk as it increases the risk of cramps, heat exhaustion, and life-threatening heatstroke. To judge the risk of exercise-induced heat illness, it is important to have a measure of heat stress. Environmental temperature is only part of this heat stress. The heat index takes into account humidity as well and is therefore a better indicator of heat stress than temperature. However, the heat index still does not take into account all factors and radiation heat, for examples, is ignored. The heat index might therefore be suitable for shade and light wind conditions, but not for more exposed conditions. The Wet Bulb Globe Temperature (WBGT) is a more accurate measurement for situations with direct sunlight. The WBGT takes into account factors like solar radiation, as well as temperature and humidity. In order to measure WBGT one needs a WBGT meter.

Heat stress

Heat stress can be challenging for the cardiovascular system and in extreme cases can be life threatening. Several heat illnesses are distinguished with different heat cramps, heat exhaustion and heat stroke.

Heat cramps: exercise-induced muscle cramps that seem to occur more often in hot conditions. There is, however, no link with core temperature.

Heat syncope: Dehydration, fatigue, tunnel vision, pale or sweaty skin, decreased heart rate, dizziness, light headedness, fainting.

Heat exhaustion: Normal or elevated body temperature (37-40 °C), dehydration, dizziness, light headedness, headache, diarrhoea, decreased urine output, persistent muscle cramps, pallor, profuse sweating, chills, cool clammy skin, intestinal cramps, urge to defecate, weakness, hyperventilation

Exertional heat stroke: Body temperature (>40 °C), drowsiness, dizziness, behavioural changes, confusion, disorientation, light headedness, headache, diarrhoea, vomiting, dehydration, hot skin, hypotension, weakness, hyperventilation

Treatment/immediate actions

- **Heat syncope**
 - Remove from training or competition
 - Allow player to rest in shade, fan and spray water
 - Loosen or remove clothing
 - Provide sips of water
 - Monitor temperature and check for mental confusion
- **Heat exhaustion or heat stroke**
 - Immediately call for an ambulance or emergency services
 - Lay the player down in the shade with legs elevated
 - Undress the player as much as possible
 - Pour water over the player and fan
 - Cool by best means possible, water immersion, ice packs
 - If patient is conscious give sips of water
 - Monitor airways and breathing

Apart from effects on performance, heat can have an effect on health. Heat cramps (involuntary spasms of the muscle that occur more in the heat) are often reported. The most common heat illness is heat exhaustion. The cardiovascular system is adjusted but these adjustments are insufficient to regulate temperature properly, often central blood volume drops, venous blood return drop, blood pressure drops as well. Other symptoms include headache, nausea, dizziness, goose bumps, and general weakness.

Below are some recommendations for organizers of races or, in this case, for football trainers. These are the guidelines from US Soccer (Figure 6). First, WBGT should be calculated from data obtained from the weather forecast. This table can be used for recommendations on how to schedule practice. There are two regions in the USA, southern regions where the players will be more acclimated to the heat can tolerate slightly higher temperatures (CAT3), but northern regions should take action at slightly lower temperatures. The advice is to have more breaks, reduce the duration of practices or move practices to a cooler part of the day.

Figure 6: Heat guidelines for football training by US Soccer

CAT I	Alert Level	WBGT by region (*F)			Event conditions	Recommended work to rest ratios (actions & breaks)
		Cat 1	Cat 2	Cat 3		
>31°C	Black	>86.2°	>89.8°	>92.0°	Extreme conditions	No outdoor training, delay training until cooler, or cancel training.
29-30°C	Red	84.2-86.1°	87.8-89.7°	90.1-91.9°	High risk for heat related illness	Maximum of 1 hours of training with 4 by 4 minute breaks within the hour. No additional conditioning allowed.
27-29°C	Orange	81.1-84.1°	84.7-87.7°	87.1-90.0°	Moderate risk for heat related illness	Maximum of 2 hours of training with 4 by 4 minute breaks each hour, OR a 10 minute break every 30 minutes of training.
25-27°C	Yellow	76.3-81.0°	79.9-84.6°	82.2-87.0°	Less than ideal conditions	3 separate 4 minute breaks each hour, OR a 12 minute break 40 minutes of training.
<25°C	Green	<76.1°	<79.8°	<82.1°	Good conditions	Normal activities. 3 Separate 3 minute breaks each hour of training, OR a 10 minute break every 40 minutes.

US Soccer recognize to recover: heat guidelines

Source: U.S. Soccer, 2018. <https://bit.ly/2Q9UiK5>