Chapter 2

Thermal strain and cooling: overview

2.1 Heat strain

The potential pathways for heat loss are evaporation, convection, conduction and radiation (McArdle *et al.,* 2001). To maintain the body core temperature within narrow limits around 37 °C heat loss has to equal heat production. Such thermal equilibrium can be described with the heat balance equation ($W \cdot m^{-2}$):

$$M - W = \pm C \pm R \pm E \pm K \pm S \qquad \text{(Eq. 1.1)}$$

M: metabolic heat production,
W: external work,
C: convective heat gain or loss,
R: radiative heat gain or loss,
E: evaporative heat gain or loss,
K: conductive heat gain or loss,
S: change in body heat storage.

The heat exchange by convection and radiation depends on the temperature difference between the body surface and, respectively, air temperature and mean radiant temperature. The evaporative heat loss depends on the difference of the vapour water pressure between the skin surface and the environment. Convection and evaporation also depend on the wind speed. At an air temperature of about 35 ºC the skin temperature becomes almost equal to the air temperature and the dry heat transfer by convection and radiation is not taking place. In that case, the heat is lost exclusively throughout sweat evaporation (evaporative heat loss). For high air/radiant temperatures and/or strenuous exercise, the evaporative heat loss might be too low. As a consequence, the body core temperature starts to rise, which has been shown to result in decreased exercise performance (Nielsen, 1996).

Nowadays, two theories try to explain the underlying mechanisms of limited exercise performance in hot environments. The first, a "critical body core temperature" theory is based upon exercise conducted under a constant workload. It suggests that the exercise is limited when the body core temperature reaches "critical values" of about 40 °C. Above this temperature, the central drive for exercise is reduced, hence volitional fatigue occurs. The second, an "anticipatory regulation of performance" theory is based upon self-paced exercise. It suggests that the excessive rise in body core temperature already in advance decreases the exercise performance. Thus, the performance is not limited, but only regulated to enable the completion of the exercise performance (Tucker, 2008).

2.1.1 "Critical body core temperature" theory

It seems that endurance exercise performance is primarily limited due to changes in the central neural system, reflected as a central fatigue. This is observed when the body core temperature during the exercise exceeds 40 °C. Nevertheless, during short high-intensity exercise, decreased oxygen delivery to the exercising muscles might play the primary role in limiting the performance. During such exercise the cardiac output decline results in muscle blood flow decrease. Thus, increased oxygen extraction cannot compensate for the reduced oxygen delivery (Nybo, 2008).

For endurance exercise performance Gonzalez-Alonso *et al.* (1999) showed that participants fatigue at similar body core temperature (~ 40 °C), regardless of initial body core temperature or the rate of body core temperature increase. Nybo and Nielsen (2001) suggested that for such exercise the body core temperature is likely to be the primary input limiting the performance. To investigate this, they instructed the participants to perform maximal voluntary contraction (MVC) of knee extensors and handgrip contractions following two different protocols. On one occasion, the MVC was repeated several times and on the other, the MVCs were sustained. This was performed with the participants being hyperthermic (~ 40 °C body core temperature) or normothermic (~ 38 °C body core temperature). They showed that the ability to generate force during sustained MVC is greatly reduced with hyperthermia. Since the maximal muscle force was the same on both occasions, they suggested that the capacity of the skeletal muscle is not affected by the hyperthermia. Instead, it seems that impaired central activation is likely to be responsible for observed decreases in sustained MVC. By investigating the brain activity, which is by measuring the electroencephalographic activity in hot environments with exercising until exhaustion, Nielsen *et al.* (2001) showed that the brain activity decreases when body core temperature progresses to 40 °C. On the other hand, when the exercise is conducted in cool environments, where the body core temperature levels off at 38 °C, a plateau in brain activity is observed. They thus confirmed that a high body core temperature has indeed the potential to alter the function of the central nervous system. The altered function could be ascribed to the interaction between direct action of the temperature on brain and indirect action of the temperature through afferent signals from skeletal and cardiac muscle, and internal organs. Furthermore, there is also growing evidence on the effect of various neurotransmitter systems, in particular dopaminergic system, to fatigue (Nybo, 2008).

During exercise in the heat, the blood is redistributed from central to peripheral regions. Thus, heart rate has to increase to provide adequate cardiac output. When hyperthermia develops, the cardiac output is affected due to decreased stroke volume. This becomes particularly apparent when short high-intensity exercise is performed, when high levels of hyperthermia are approached and when dehydration occurs. As a consequence, decreased cardiac output results in decreased muscle blood flow (Nybo, 2008; Gonzalez-

Alonso *et al.*, 1998). Yet, during submaximal exercise the muscle oxygen utilization remains unchanged. Furthermore, minor elevations in lactate release and glycogen utilization are observed at the point of fatigue. Nevertheless, at this point the depletion of glycogen stores is not observed (Febbraio, 2000). Thus, it can be concluded that the changes in the metabolism are not responsible for hyperthermia induced fatigue. On the other hand, during short high-intensity exercises muscle oxygen utilization decreases and consequently the anaerobic metabolism markedly increases. Thus, short high-intensity exercise is limited due to decreased muscular oxygen utilization and homeostatic disturbances caused by anaerobic metabolism (Nybo, 2008).

In summary, during short high-intensity exercise the reduced performance is likely to be related to the failure in muscle's oxygen utilization. During endurance exercise, however, the reduced performance is likely to be ascribed to the failure of the brain to sustain muscle activation.

2.1.2 "Anticipatory regulation of performance" theory

"Anticipatory regulation of performance" is a phenomenon observed when participants are allowed to self-pace the exercise. On such instances, the results on physiological responses induced by heat stress are likely to be different as those described in previous sub-section.

Tatterson *et al.* (2000) investigated the effect of exercising in hot environments on self-paced exercise. They instructed the participants to perform 30 min self-pace exercise at 23 and 32 °C environmental temperature and at the same relative humidity (60%). They observed a 6.5% reduction in a power output when exercise was performed in hot environments, whereas the body core temperature increase was similar. In fact, when exercising at 32 °C the participants decreased the power output already after the first 10 min of the exercise. Thus, the authors concluded that the participants select the intensity of the exercise which enabled them to sustain the body core temperature below the critical limit. Furthermore, Marino *et al.* (2004) showed that the African runners, who have a lower rate of body heat storage increase, outperform the Caucasian runners in the heat. However, both African and Caucasian runners completed the running with similar body core temperature. Also in the study of Tatterson *et al.* (2000) the rise in body core temperature did not differ between the African and Caucasian runners. Tucker *et al.* (2004) showed that when self-paced exercise is performed, the skeletal muscle recruitment and thereby work output is down regulated before the body core temperature is even elevated significantly. This enabled thermal homeostasis to be maintained during both hot (35 °C) and cool (15 °C) environmental conditions. Consequently, the body core temperature was not different between the conditions until the 15 km of the exercise. Afterwards, the body core temperature differed but did not reach typical "critical" values. Therefore, Tucker *et al.*

(2004) suggested that an early decline in power output forms a part of an anticipatory response in the brain. This response mediates a reduction in skeletal muscle recruitment to ensure that the rate of heat production is reduced. Thereby, the attainment of critical body core temperature is avoided and the exercise completed without premature fatigue. If this is true, than the rate of increase in body heat storage is a crucial afferent input to a central controller which in turn adjusts the work rate. This assumption is supported by the study of Marino *et al.* (2000) who showed that in hot environments, lighter runners outperform heavier runners during self-paced 8 km run, following 30 min running at 70% peak treadmill speed. They suggested that lighter runners outperform heavier runners since they store less heat at the same running speed. Nevertheless, it remains unclear how the brain detects the initial increase in heat storage at hot environmental conditions. Tucker *et al.* (2004) suggests that afferent sensory input from the thermoreceptors in the skin must form part of integrated response that mediates decreased power output.

In summary, the studies reviewed show that the self-paced exercise is regulated in order to secure the completion of the exercise. However, the specific mechanisms by which the anticipatory mechanism functions awaits further explanations.

2.2 Preventing heat strain

The decrease in exercise performance, self-paced or conducted at constant work load, is in practise mainly counteracted with proper hydration, acclimation and cooling (Hargreaves, 2008). In the following sub-sections a review on the hydration (2.2.1) and acclimation (2.2.2) methods is provided. Then, a detailed overview of the work investigating the effect of cooling prior to exercise i.e. pre-cooling on exercise will follow (2.2.3). This section will conclude with information on cooling provided after the exercise to the decrease the heat strain and to promote the regeneration (2.2.4).

2.2.1 Hydration

Dehydration equal to or exceeding a loss of 2% (euhydrated) body mass is shown to have a negative effect on exercise performance (Murray, 2007). This becomes even more apparent when exercise performance is conducted in hot environments. In such environments, the dehydration worsens heat dissipation by reducing the skin blood flow (Kenney *et al.*, 1990) and local sweating (Bittel & Henane, 1975). This can result in excessive rise of body core temperature, where for every percent of body weight decrease, the body core temperature will increase by 0.1 - 0.25 °C (Sawka *et al.*, 2001; Montain & Coyle, 1992). Thus, appropriate hydration is a prerequisite for the prevention of excessive increases in body core temperature and early fatigue when exercising in hot environments.

Appropriate hydration can be provided by fluid ingestion prior to (prehydration), during or after the exercise. Prehydration enables to start the exercise in euhydrated state and with plasma electrolytes at normal levels. According to the position stand of the American College of Sports Medicine (ACSM) (2007), prehydration should be achieved by consuming sufficient beverages with meals and a recovery period of 8 - 12 h since the last exercise. When prehydrating, the individual should drink about 5 - 7 $ml \cdot kg^{-1}$ of fluid at least 4 h before the exercise. If the urine produced is insufficient or dark (highly concentrated), more fluid, that is 3 - 5 $ml \cdot kg^{-1}$, should be drunk about 2 h before the exercise. A mode of prehydration is also hyperhydration, where fluids that expand extra- and intracellular spaces (e.g. water and glycerol solutions) are ingested. However, this method is shown not to have any advantageous effects on exercise performance. In fact, it can increase the risk of voiding during the competition and, as emphasised by Noakes *et al.* (2005); excessive drinking prior to the exercise can lead to dilutional hyponatremia and potential death. Thus, ingesting amounts of beverages higher than recommended should be avoided. During exercise sweat loss should be matched with fluid replacement. Since the feeling of thirst is not perceived until 2% body mass is lost, ad libitum water intake when exercising in hot environments is likely to result in an incomplete fluid replacement. In fact, voluntary fluid ingestion generally approximates only 50% of sweat losses even on occasions when fluid is available (Murray, 1996). Since many factors (e.g. weather conditions and clothing) will affect the sweating rate, the individual should monitor body weight changes during training/competition to estimate the sweat rate under conditions expected. Such an approach enables customized ingestion of fluids and best prevents dehydration under expected conditions. The consumption of fluids after the exercise depends on the speed that rehydration needs to be taken and on the magnitude of the dehydration. In the case when fast recovery is needed the individuals should drink about 1.5 l of fluid for each kilogram of body weight loss. Intravenous fluid replacement might be provided to severely dehydrated individuals with more than 7% body weight loss.

Exercise performance in hot environments is shown to cause dehydration which furthermore elicits increases in body core temperature. This can be counteracted with appropriate hydration prior, during or after the exercise. Nevertheless, care must be taken from excessive fluid ingestion prior to the exercise which can lead to dilutional hyponatremia and potential death.

2.2.2 Acclimation

Repeated exposures to hot (dry or humid) environments are shown to reduce physiological strain and to improve exercise performance. Physiological adjustments are referred to as acclimatisation responses when induced in naturally occurring environments and acclimation responses when induced in controlled environmental settings (Pandolf, 1998). For the purpose of this thesis the term acclimation is used in all cases.

Heat acclimation can be induced with exposures to dry or humid heat, as well as with a physical activity (Nielsen, 1998, 1994). Nearly complete acclimation for both dry and humid heat is reported to occur after 7 - 10 days, whereas up to 75% of adaptation is observed already within 4 - 6 days (Pandolf, 1998). Early acclimation responses include improvements in cardiovascular function (increased plasma volume and decreased heart rate), autonomic system (redirected blood to the skin and muscles) and perceived exertion. Specifically, plasma volume is reported to expand for up to 10% (Nielsen, 1998). This expansion is likely to decrease after 8 - 14 days, unless the physiological strain during the acclimation process is maintained using increments in exercise intensity (Taylor, 2000). Expansion in plasma volume results in increased stroke volume and decreased heart rate. For instance, Nielsen *et al.* (1993) reports decreases in heart rate from 164 ± 6 to 153 ± 6 bpm within 9 -12 days of acclimation. These cardiovascular responses furthermore allow an increase in skin blood flow. Another important heat dissipation mechanism being affected during acclimation process is sweating. It may increase two-fold and is the result of the increased steady state sweat rate and reduced sweating threshold. Enhanced skin blood flow and sweating alter heat transfer which is reflected in decreased body core temperature. The body core temperature can decrease for 0.2 to 0.8 °C (Kampmann *et al.*, 2008). Collectively, the physiological adaptations described lead to a decrease in perception of effort and an increase in exercise performance. For instance, Nielsen *et al.* (1993) observed an increase in endurance time from 48 ± 2 to 80 ± 3 min. Although it is well established how fast acclimation occurs, there is no consensus on the rate of acclimation decay. Givoni and Goldman (1973) proposed that with each two non acclimation days and equivalent of one acclimation day is lost. Furthermore, the first physiological responses lost, are the one that occur first in the process of acclimation (Pandolf, 1998; Williams *et al.*, 1967).

Acclimation can be achieved by natural acclimatisation (living in hot environments), passive heat acclimation, exercise induced heat adaptation and with combined exercise and heat acclimation (Taylor & Cotter, 2006). Natural acclimatisation is associated with long term residence in hot environments and represents the most effective means of increasing the heat tolerance. Passive heat acclimation is evoked by passively increasing the body temperature using for instance sauna, hot baths and climatic chambers. Exercise induced heat adaptation is achieved with sustained and repeated elevations in body temperature induced by exercise. Combined exercise and heat acclimation (exercise-heat acclimation) are the optimal approximation to natural acclimatisation. To induce exercise-heat acclimation, exercise of moderate to heavy intensities is conducted in a climatic chamber controlled at defined temperatures and relative humidity. Specifically, exercise can be conducted either at constant work load, it can be self-paced or conducted at controlled hyperthermia regimens. It seems that the later regime, where the work load is adjusted to maintain targeted body core temperature, induces the most complete heat adaptation (Regan *et al.*, 1996). Specifically, Armstrong (2000) suggests exercising at intensities greater than

50% of the maximal oxygen consumption. Total exposure should last 90 - 100 min, where the time should be reached gradually within 10 - 14 days. According to Taylor (2000) the environmental temperature selected should be close to that anticipated at the competition setting. Nevertheless, the upper limit for dry heat should be 50 °C and for the humid heat 40 °C. Relative humidity should be chosen to the highest anticipated. Elevations in body core temperature should be higher than 1 °C; however they should not exceed 39.5 °C (Taylor, 2000).

Successive heat exposures are shown to successfully counteract limited exercise performance in hot environments. In laboratory settings this is most efficiently achieved with exercising under hot environments. Nevertheless, in the process of successive heat exposures, in particular during the first days, care must be taken to avoid the risk of heat exhaustion.

2.2.3 Pre-cooling

Pre-cooling became a focus of scientific research with Olympic Games being conducted under hot and humid environmental conditions. This was the case at the 1996 Olympic Games in Atlanta, Georgia and the 2004 Olympic Games in Athens, Greece. Nevertheless, the idea of pre-cooling was conceived much earlier. Veghte and Webb (1961) hypothesized that in effort to extend human tolerance in hot environments, the possibility of using an altered physiological state, such as a lower body core temperature, might have a merit. This assumption based on the work of Schmidt-Nielsen *et al.* (1957) who reported that decreased body core temperatures during the night enables the camel to decrease body core temperature increase during the day. Inspired by this observation, Veghte and Webb (1961) submitted the participants first to cooling of various temperatures and durations. Afterwards, the participants were submitted to a rest in hot environment until their maximal tolerance time to heat was reached. The results of the study showed that cooling prior to exposure to the hot environment increased the tolerance time. In fact, they reported that the greater the decrease in body temperature, the larger the increase in the tolerance time.

The work of Veghte and Webb (1961) was followed by many studies investigating the effects of different pre-cooling methods on different types of exercise performance. Sub-sections from 2.2.3.1 to 2.2.3.3 provide an overview of studies investigating the effect of pre-cooling on high-intensity, endurance and intermittent exercise performance. In each part explanation on possible underlying mechanism responsible for improving or not improving the exercise performance is given. Furthermore, in sub-sections 2.2.3.4 effect of pre-cooling on disabled individuals, such as those with spinal cord injury and multiple sclerosis, is provided. This section concludes with information on the methods of pre-cooling (2.2.3.5) and possibilities of increasing the efficiency of pre-cooling (2.2.3.6).

2.2.3.1 The effect of pre-cooling on high-intensity exercise performance

Only a few studies are published on the effect of pre-cooling on high-intensity exercise performance. This might be since thermoregulation during such type of exercise plays only a minor role. Some authors (Sleivert *et al.*, 2001; Marsh & Sleivert, 1999), however, hypothesized that pre-cooling would decrease the skin blood flow and thereby shift the blood from the peripheral (skin) to the central (body core) regions. Consequently, after the pre-cooling more blood would be available for the working muscles. Thus, improved exercise performance would base on increased oxygen delivery and removal of metabolites for the working muscles. Table 1.1 provides a summary of the studies where the effect of pre-cooling on high-intensity exercise was investigated. These studies show that in general pre-cooling does not impose a positive effect. As suggested by Sleivert *et al.* (2001) this is likely to be ascribed to reduced muscle temperature and thereby affected muscle contractile function.

Table 1.1 *Summaries of the studies investigating the effect of pre-cooling on high- intensity exercise.* T_a *is the air temperature; RH is the relative humidity;* T_w *is the water temperature;* T_c *is the body core temperature; PO is the power output; ↓ denotes a decrease and ↑ denotes an increase in the exercise performance*

Reference	Pre-cooling method	Exercise	T_a & RH	Exercise outcomes
Bergh and Ekblom (1979)	15 - 25 min swimming T_w = 13-15 °C	all out arm and leg ergometer exercise	20 - 22 °C	time until exhaustion ↓
Crowley *et al.* (1991)	30 min leg immersion T_w = 11.5 - 12.2 °C	30 s all out cycling	*no data*	26% ↓ in mean PO 30% ↓ in peak PO
Marsh and Sleivert (1999)	30 min or T_c ↓ = 0.3 °C torso immersion T_w = 12 - 14 °C	70 s all out cycling	29 °C 80%	3.3 ± 2.7% ↑ in mean PO
Sleivert *et al.* (2001)	45 min torso with or without leg cooling at T_a = 3 °C	45 s all out cycling	33 °C 60%	torso: no effect torso with leg: ↓ in mean and peak PO
Mitchell *et al.* (2003)	20 min whole body air cooling combined with water spraying	all out running	38 °C 64%	time until exhaustion ↓

2.2.3.2 The effect of pre-cooling on endurance exercise performance

The majority of the studies on pre-cooling investigated its effect on endurance exercise performance. It is hypothesised that improvements in the performance occur due to decreased initial body heat storage (Marino, 2002). Table 1.2 provides a summary of the studies investigating the influence of pre-cooling on endurance exercise performance. In general, it can be concluded that pre-cooling indeed improves endurance exercise performance. This is mainly reflected in increased time-to-exhaustion, in total maximum work performed in a fixed time, or in the self-paced distance run or cycled in fixed time.

Few studies focused on the investigation of the underlying mechanisms responsible for the improvements of endurance exercise performance. Olschewski and Bruck (1988) observed a decreased heart rate and increased oxygen pulse (amount of oxygen used per heart rate). However, with heavy exercise these changes diminished. Similarly, Hessemer *et al.* (1984) observed an increase in oxygen pulse. In the latter case, however, no changes in heart rate were observed. Collectively, these studies suggest that the underlying mechanisms for increases in exercise performance due to pre-cooling might be a reduction in cardiovascular and metabolic strain. Nevertheless, Kay *et al.* (1999) emphasized the role of the central nervous system in response to or in anticipation of changes in body heat storage. They suggested that the key mechanisms for performance decrement are located in the central nervous system and result in a reduction of muscle activation in response to increased body heat storage as described in sub-section 2.1.2. Thus, as a response to pre-cooling and thereby a decrease in body heat storage, the central nervous system allows higher exercise intensities in particular when self-paced exercise is performed (Tucker, 2008). It is can be concluded that underlying mechanisms responsible for improving endurance exercise performance due to pre-cooling are not fully understood. Thus, further work needs to be performed to identify such mechanisms.

Table 1.2 *Summaries of the studies investigating the effect of pre-cooling on endurance exercise performance.* T_a *is the air the temperature; RH is the relative humidity;* T_c *is the body core temperature;* T_w *is the water temperature; GXT is graded exercise test;* $\dot{V}O_{2max}$ *is maximal oxygen consumption; PO is power output; ↓ denotes a decrease and ↑ denotes an increase in the exercise performance.*

Reference	Pre-cooling	Exercise	T_a & RH	Exercise outcomes
Schmidt and Bruck (1981)	2 whole body cold air exposures T_a = 0 °C until shivering	cycling, GXT until exhaustion	18 °C	no effect on time to exhaustion and maximum work rate
Hessemer *et al.* (1984)	2 whole body cold air exposures T_a = 0 °C until shivering	55 min cycling at 50 - 60% $\dot{V}O_{2max}$ last 5 min all-out	18 °C	6.8 % ↑ in mean work rate
Olschewski and Bruck (1988)	2 times 15 min whole body cold air exposure T_a = 5 - 10 °C	cycling, GXT until 80% $\dot{V}O_{2max}$, than until exhaustion	18 °C 5%	12% ↑ in time to exhaustion
Lee and Haymes (1995)	33 min whole body cold air exposure T_a = 5 ± 1 °C	running at 82 % $\dot{V}O_{2max}$ until exhaustion	24 °C 51 - 52%	21% ↑ in time to exhaustion
Booth *et al.* (1997)	60 min whole body immersion T_w = 23 - 24 °C or until shivering	30 min self paced running	31.6 °C 60%	4% ↑ in distance run
Kay *et al.* (1999)	58.4 ± 1.4 min whole body immersion T_w = 25.8 ± 0.2 °C	30 min self paced cycling	31.4 °C 60%	6% ↑ in distance run
Cotter *et al.* (2001)	45 min ice-vest and/or cooling thighs at T_w = 3 °C	20 min cycling at 65% $\dot{V}O_{2max}$ than 15 min all-out	33 °C 60%	ice-vest 17.5% ↑ and ice-vest and thighs 16% ↑ in overall PO
Arngrimsson *et al.* (2004)	38 min ice-vest during the warm up	5 km self paced running	32 °C 50%	1% ↑ in running time
Hasegawa *et al.* (2005)	30 min prior to and 60 min ice-vest during warm up	cycling at 80% $\dot{V}O_{2max}$ until exhaustion	32 °C 78 - 80%	2-fold ↑ in time to exhaustion
Daanen *et al.* (2006)	45 min water perfused suit on upper and/or lower body T_w = 5°C	40 min cycling at 80% $\dot{V}O_{2max}$	30 °C 70%	no effect on gross cycling efficiency
Webster (2005)	25 min ice-vest during warm up	10 min running at 70% $\dot{V}O_{2max}$, than at 95 % $\dot{V}O_{2max}$	37 °C 50%	42 % ↑ in time to exhaustion

Reference	Pre-cooling	Exercise	T_a & RH	Exercise outcomes
Uckert and Joch (2007)	20 min ice-vest	running, GXT until exhaustion	30 - 32 °C 50%	7% ↑ in time to exhaustion
Duffield *et al.* (2010)	20 min water immersion of lower body $T_w = 14 \pm 0.3$ °C	40 min self paced-cycling time trial	33 °C 50%	11% ↑ in mean power

2.2.3.3 The effect of pre-cooling on intermittent exercise performance

Intermittent exercise is characterized by bouts of high-intensity exercise separated by pauses which are not necessary static and can incorporate exercise of light to high intensity. This exercise pattern can be observed in team sports and intermittent sprint exercise. For this type of exercise performance, cooling can be provided prior to the exercise and during the breaks between the bouts of exercise. Drust *et al.* (2000) hypothesized that during intermittent exercise performance, the body core temperature is likely to increase to a greater degree compared to a continuous exercise. This is since physiological responses to an intermittent activity are characterised by higher levels of physiological strain than those associated with continuous exercise performed at the same mean work rate (Ranalli *et al.*, 2010). Thus, the need for pre-cooling when performing intermittent exercise performance might be even higher compared to the continuous exercise performed at the similar average intensity. When investigating the effect of pre-cooling on intermittent exercise performance, traditionally sprint efforts as the only measure of performance was investigated. Such studies, reviewed in the table 1.3, with exception of Castle *et al.* (2006), do not show any positive effect. However, Duffield and Marino (2007) in addition to sprint efforts also investigated self-paced sub-maximal performance that followed sprint efforts and observed improvements. Furthermore, positive effects of pre-cooling were also observed when only self-paced exercise was conducted (Peiffer *et al.*, 2010; Duffield *et al.*, 2009). Thus, it might be that pre-cooling increases self-paced exercise performance, but not maximal sprint efforts.

Table 1.3 *Summaries of the studies investigating the effect of pre-cooling on intermittent exercise performance.* T_a *is the air temperature; RH is the relative humidity;* T_c *is the body core temperature;* T_m *is the muscle temperature;* T_w *is the water temperature;* $\dot{V}O_{2max}$ *is maximal oxygen consumption PO is power output; ↓ denotes an decrease and ↑ denotes an increase in the exercise performance.*

Reference	Pre-cooling	Exercise	T_a & RH	Exercise outcomes
Drust *et al.* (2000)	60 min shower, T_w decreased from 28-24 °C	soccer specific exercise (2x45 min)	21 °C 68%	no effect on the distance covered
Duffield *et al.* (2003)	ice-vest prior to and after exercise	field hockey specific exercise (3 x 15 min)	30 °C 60%	no effect on mean total work done and PO
Cheung and Robinson (2004)	water perfused suit with T_w = 5 °C 75 min or until T_c ↓ = 0.5 °C	cycling 30 min at each 5 min sprint and rest	22 °C 40%	no effect on peak and mean PO
Castle *et al.* (2006)	20 min of ice-vest, or immersion T_w = 17.8 °C or ice packs	20x2 min exercise i.e. 10 s rest, 5 s sprint	34 °C 52%	when ice packs on thighs 4% ↑ in peak PO
Duffield and Marino (2007)	ice -vest with/without preceding cold bath T_w = 14 °C, 15 min prior exercise, during warm	2x30 min intermittent exercise with 10 min recovery	32 °C 30%	no effect
Duffield *et al.* (2009)	combination of ice-vest, 0.6 kg ice bags for thigh cooling and cold towels previously immersed in T_w = 3°C	4x5 min free paced intermittent-sprint exercise	32 °C 44%	8% ↑in the distance covered
Peiffer *et al.* (2010)	5 min of cold water immersion with T_w = 14°C	2x25 min of constant paced exercise equal to 65% $\dot{V}O_{2max}$ followed by 4 km time trial	35 °C 40%	13% ↑ in PO during constant pace exercise and 4% ↑ distance covered in time trial

2.2.3.4 *Pre-cooling in disabled individuals*

Pre-cooling can be of interest for disabled individuals, such as those with spinal cord injury (SCI). In SCI individuals the control of heat dissipation system such as sweating is impaired (Price, 2006). Since SCI individuals are bounded to a wheelchair the weight of the cooling-system plays a less important role compared to the able-bodied individual. During wearing ice-vest wheelchair propulsion is suggested to be only mildly impaired. Studies investigating the effect of cooling for SCI individuals mainly investigated the effect of cooling on thermophysiological responses rather than on exercise performance. For instance, Hagobian *et al.* (2004) showed that a foot cooling device based on negative pressure reduces the rise in tympanic temperature. Webborn *et al.* (2005) in addition to pre-cooling studied also the effect of cooling during the exercise. They showed that both strategies result in reduced heat strain during the exercise. Furthermore, Goosey-Tolfrey *et* *al.* (2008) provided hand cooling between two bouts of exercise and showed that such approach might be useful for intermittent recovery. Armstrong *et al.* (1995) investigated the effect of cooling, using ice-vest and cooling headpiece, on exercise performance. Although they observed decreases in body heat storage, improvements in exercise performance were not observed. The reviewed work shows cooling prior to or during the exercise might be useful to reduce heat strain in SCI individuals. However, it remains unclear if cooling increases also exercise performance.

Patients with multiple sclerosis (MS) are likely to benefit from cooling prior to or during the exercise as well. These patients often report worsening of the neurological symptoms with small increases in body temperature, but improvements with cooling. The effect can be quite dramatic, for instance with improvements in vision upon drinking of a glass of cold water (Smith & McDonald, 1999). Davis (1970) suggested that such improvements due to cooling are induced by a small prolongation in action potential duration along the unaffected parts of neurons. The prolongation lengthens the time period of opened sodium channels, which favours successful action potential conduction (Rutkove, 2001). Thus, despite a relatively low sodium channel density in the neuron underneath the lesion, the polarization and thereby the conduction of neural information, is promoted (Smith & McDonald, 1999). The literature investigating the effect of cooling in MS patients is mainly focusing on neuroperformance reflected in coordination, gait and postural control. The outcomes of these studies show that cooling has beneficial effects (Beenakker *et al.*, 2001; Kinnman *et al.*, 1997; Watson, 1959). The literature on the effect of cooling during the exercise in MS patients is however scarce. Since exercise is related to increases in body temperature it cannot be excluded that application of cooling prior to or during the exercise would improve the performance.

2.2.3.5 Methods of pre-cooling

The most common pre-cooling methods used in laboratory settings have been cold air exposure and water immersion. For instance Schmidt and Bruck (1981) and Hessemer *et al.* (1984) used a climatic chamber and exposed their participants twice to air with a temperature of 0 °C. The exposure was terminated soon after the onset of shivering and was followed by rewarming. Similarly, Olschewski and Bruck (1988) exposed the participants to an air temperature of 18 °C, where this temperature was subsequently decreased to 5-10 °C, within 15 min. Then, the temperature was increased until the oxygen uptake of the participants returned to the levels prior to cold exposure. Subsequently, another identical cold exposure followed. In the study of Lee and Haymes (1995) the participants were exposed to air temperatures of 5 ± 1 °C for ~ 33 min. Mitchell *et al.* (2003) did not provide cooling using cold air, instead the cooling was provided for 20 min in air temperature of 22 °C. Cooling was however induced by rotating the participants every 2 min for 180° while being sprayed with 100 ml water. Cooling was furthermore enhanced with constant air flow of 4 m·s^{-1} over the participants. To summarize, these studies shows that cooling with cold air is usually administered using climatic chambers, with air temperatures lower than 10 °C and exposure times up to about 30 min. To decrease thermal discomfort of the participants, some authors spaced the consecutive cold air exposures with rewarming.

For water immersion, the accompanying thermal discomfort was avoided with gradually decreasing the water temperature (Kay *et al.*, 1999; Booth *et al.*, 1997). Booth *et al.* (1997) initially immersed their participants into the water temperature of 28 - 29 °C. After 10 min water was siphoned out and replaced with cold water so that the water temperature settled between 23 - 24 °C. The water immersion lasted for 60 min or until the continuous shivering occurred. Bergh and Ekblom (1979) approached water immersions with instructing the participants to swim for 15 - 25 min in water temperature of 13 - 15 °C. Bolster *et al.* (1999) immersed their participants into water of about 26 °C until a decrease in body core temperature of 0.5 °C was observed. To achieve this, the immersions lasted on average for about 30 min, whereas individual cooling times varied from about 19 to 63 min. To avoid cooling of the major muscles group needed for the exercise Marsh and Sleivert (1999) applied water immersion only to the torso, whereas the legs were removed from the water. The initial water temperature was 18 °C, which was lowered to 12 - 14 °C after 5 min using crushed ice. The water immersions lasted for 30 min or when a drop in body core temperature of 0.3 °C was observed. Unlike Marsh and Sleivert (1999), Crowley *et al.* (1991) and Wilson *et al.* (2002) aimed at cooling the muscles involved in the exercise. Crowley *et al.* (1991) provided cooling to the legs with instructing the participants to sit (the water reached to the waist level) in a water tank with about 12 °C water temperature for 30 min. In the study of Wilson *et al.* (2002), 30 min cooling was provided to the lower body in water temperature of 17.7 ± 0.5 °C. The participants were instructed to sit on a chair positioned in a large tank, where the water reached the supra-iliac crest. Partial body immersion, provided in the field and not in the laboratory settings, was investigated by Yeargin *et al.* (2006). Two different intensities of immersion were provided during two bouts of exercise. The intensities of cooling provided were cold-water immersion (13.98 ± 0.31 °C) and ice-water immersion (5.23 ± 0.21 °C). Each immersion lasted 12 min, with the participant being immersed from the shoulders to the upper legs. To summarize, the temperatures of the water were usually higher than 12 °C, where on some occasions, the whole body was submitted to cooling, whereas, on others, cooling of the muscles involved in the exercise was avoided. The exposure time lasted less than 60 min. Cooling using cold air exposure and water immersion are however not the suitable methods for field settings.

Studies investigating the effect of pre-cooling in field settings applied cooling vests. The functioning of the cooling vest is often based on ice-packs or frozen gels embedded in various garments. The cooling vest used by Cotter *et al.* (2001) and Sleivert *et al.* (2001) was based on a water-gel mix (~1.2l) (Cool.1.nz, Dunedin, New Zealand). The vest was applied during 45 min rest at an air temperature of 3 °C. Hasegawa *et al.* (2005) also used a cooling vest (Body Cool; Nishi Sports, Tokyo, Japan) during rest of 30 min, however at a higher air temperature of 26 °C. The cooling vest was constructed from a wet-suit (neoprene) with four anterior and four posterior pockets. Each pocket contained a flexible ice pack (350 g). Similarly, Uckert and Joch (2007) used a cooling vest (Arctic Heat, Burleigh Head, Australia) during 20 min rest, though in an even higher air temperature of 32 °C and 50% relative humidity. The cooling vest (Neptune Wetsuits Australia, Smithfield West, Australia) used by Arngrimsson *et al.* (2004) provided cooling similarly to the study of Hasegawa *et al.* (2005) through eight ice packs (400-500 ml each) positioned over chest, stomach, shoulder blades and lower back. The ice-vest was worn during 38 min warm-up, performed at an air temperature of 32 °C and 50% relative humidity. Webster *et al.* (2005) provided three distinctive cooling vests, where the heat capacity of the vests was 597.0 $J \cdot g^{-1}$, 562.3 $J \cdot g^{-1}$ and 334.5 $J \cdot g^{-1}$. Cooling was provided during rest and active warm-up at an air temperature of 37 °C and 50% relative humidity. Apart from the mentioned studies, Duffield *et al.* (2007, 2003) provided cooling prior to as well as during exercise, i.e. during the rest periods that interspaced intermittent sprint cycling exercise. The pockets embedded in the cooling vest were filled with cubed ice prior to the experiment, whereas during the rest periods the vest was placed into a cooler. Extra ice was added if needed. The exercise and thereby the cooling during the breaks was provided at an air temperature of 32 °C and 60% relative humidity. In the mentioned studies, the cooling vest was applied in laboratory settings, whereas Hunter *et al.* (2006) provided cooling (Nike Ice-Vest) about 1 h prior to the race. The cooling was provided through ice-packs loaded into 20 pouches distributed over from and back side of torso. To summarize, the weight of the cooling vests amounted to 4.5 kg in the study of Arngrimsson *et al.* (2004), to 4.4 kg in the study of Hunter *et al.* (2006), to 3.3 kg in the study of Hasegawa *et al.* (2005) and from 2.8 to 3 kg in the study of Webster *et al.* (2005). The cooling vests can be heavy and as suggested by Arngrimsson *et al.* (2004) such weight is likely to increase the energy cost in particular if the vest is worn during active warm-up consisting of a running exercise. Furthermore, various strategies were approached to provide cooling using the cooling vest. Cooling vests were worn during warm-up or rest, at normal or high environmental temperature.

Only rarely, water-perfused cooling suits were used as a cooling method in pre-cooling studies (Daanen *et al.*, 2006; Cheung & Robinson, 2004). Daanen *et al.* (2006) used a whole-body cooling suit, however provided cooling to various body parts (whole body, torso and legs). The circulating water temperature was set to 5 °C, where cooling was provided for 45 min during rest at an air temperature of 30 °C and 70% relative humidity. In the study of Cheung and Robinson (2004) cooling was provided to torso, arms and to head (without face) (Med-Eng Inc., Pembroke, Canada) by circulating water with a temperature 5 °C at an air temperature of 22 °C and 40% relative humidity. The cooling was provided until the decrease in body core temperature by 0.5 °C was observed or for 75 min. Furthermore, in some studies cooling was provided using water perfused cuffs

(Aircast Autochill System, Aircast, NJ, USA) (Cotter *et al.*, 2001; Sleivert *et al.*, 2001). The cuffs were used to provide cooling to local areas such as the thighs.

In recent years, pre-cooling administered through ingestion of cold drinks has gained on popularity. This is since the methods discussed above are usually impractical to athletics due to problems regarding time and equipment necessary to achieve sufficient body cooling to improve exercise performance (Lee *et al*., 2008). In the study of Mundel *et al*. (2006) the participants were instructed to ingest drinks of 4 °C during exercise under environmental temperature of 33.9 ± 0.2 °C and 27.9 ± 0.7 % relative humidity. Similarly, Lee *et al*. (2008) provided drinks of 4 °C prior to and during the exercise at 35 ± 0.2 °C and 60 ± 1 % relative humidity. Furthermore, a more aggressive internal cooling method was investigated by Siegel *et al*. (2010) and Ross *et al.* (2011). Siegel *et al*. (2010) instructed the participants to ingest 7.5 g of ice slurry (-1°C) per kg of body mass prior to the exercise in the heat (34.0 ± 0.2°C, 54.9 ± 5.9% relative humidity). And Ross *et al.* (2011) instructed the participants to ingest ice, while cooling was additionally provided with placing cold towels to cover torso and legs. Specifically, the participants were asked to consume a total of 14 g of sport drink slushie per kg of body weight.

It can be concluded that various methods were used to provide cooling in the pre-cooling studies. These varied greatly in their intensity, surfaces to which cooling was provided and environmental conditions under which, cooling was provided. Although various methods were developed and assessed to provide the cooling, the investigation of the possibilities to increase the efficiency of these methods was hardly addressed.

2.2.3.6 Improving the efficiency of the pre-cooling methods

Shvartz (1970) hypothesized that the cooling efficiency would be increased with application of cooling to body regions with low vasomotor tone. To confirm this hypothesis, he compared the physiological responses initiated upon cooling the head (low vasomotor tone) with cooling larger body surface areas. The hood provided to the head covered about 12% of the body surface area, whereas the cooling suit covered approximately 72% of the body surface area. He indicated that, although the surface area was 6 times smaller, the cooling of the head was still about half as effective as cooling the larger body areas. Furthermore, based on the hypothesis that skin surface over the active muscles is warmer than other skin parts, Webb (1970) constructed a water cooling garment with higher flow over the leg muscles. Young *et al.* (1987) showed that if cooling is provided to surface areas over active muscles, the efficiency of cooling can be improved with increasing the surface areas cooled. In all these studies, the approach to increase the cooling efficiency was based on avoiding the vasomotor tone. The application of cooling causes a decrease in skin temperatures. This can initiate skin vasoconstriction with a decreased heat transfer between the body core and the environment (Cheuvront *et al.*, 2003). Veicsteinas *et al.* (1982) suggested that vasoconstriction and hence the superficial shell insulation reaches maximal values at the skin temperature of 30 °C, with vasoconstriction occurring at the temperatures between 32 and 33 °C. To avoid the initiation of vasoconstriction, Cheuvront *et al.* (2003) suggested the application of intermittent cooling. They hypothesized that the application of intermittent cooling to different body regions would reduce the vasomotor response and thereby avoid possible decreases in heat transfer from body core to the environment. Indeed, they showed that intermittent cooling represents more efficient means of removing body heat compared to the constant cooling.

In summary, studies focusing on increasing the efficiency of pre-cooling are based on avoiding the initiation of vasoconstriction response. Only little work conduced in this field might hold promise for further possibilities to improve the efficiency of pre-cooling. Part of the work presented in this thesis focused on investigating the possibilities to increase the efficiency of pre-cooling methods. It was of particular interest to focus on the method were pre-cooling is provided by personal cooling-systems that can be used in field settings.

2.2.4 Cooling after the exercise

Cooling after the exercise is of importance when exercising in hot environments causes the occurrence of heat related symptoms. Another aspect of providing cooling after the exercise is to enhance the recovery.

To decrease heat related symptoms a variety of cooling methods can be applied. The most effective is water immersion, whereby the highest cooling rates are achieved with the immersion in ice water (Smith, 2005). High cooling rates can be ascribed to a high water thermal conductivity of 0.6 $W \cdot m^{-1} \cdot °C^{-1}$, whereas thermal conductivity of air amounts to 0.025 $W \cdot m^{-1} \cdot °C^{-1}$. Furthermore, considering the specific heat and the density of water, it is expected that a person would cool four times faster in water compared to air (Casa *et al.*, 2007). The cooling rates achieved with water immersion are reported to range between 0.15 to 0.50 $°C \cdot min^{-1}$ (Proulx *et al.*, 2003; Armstrong *et al.*, 1996; Costrini, 1990). Proulx *et al.* (2003) investigated the effect of different water temperature on cooling rate and found no differences when water temperature amounted to 8, 14 or 20 °C. However, the cooling rate was two times higher with immersion to 2 °C water temperature. Furthermore, Taylor *et al.* (2008) investigated a more conservative approach and immersed hyperthermic individuals to 26 °C water temperature. They did not observe any difference in cooling rates between 26 and 14 °C water temperature. This is of practical significance since in emergency situations one might not be able to provide very low water temperature. Furthermore, also the immersion of only separated body parts, such as hands, are shown to decrease heat strain, where lower water temperature is reported to be more efficient (House *et al.*, 1997). Heat related symptoms can also be decreased with removal of clothing, spraying tepid water over the body, and facilitating evaporation and convection with the use of a fan

(Smith, 2005). Less used methods to decrease heat strain after the exercise include the placements of ice packs, massaging with the ice, placing wet towels over the entire body, face fanning and application of cooling vests. Barwood *et al.* (2009) compared some of these methods (hand immersion, vest with phase change material, liquid cooling garment and whole body and face fanning) and concluded that whole body fanning was the most effective form of cooling the hyperthermic individuals. Invasive methods of cooling such as gastric lavage were mainly investigated in animals, whereas data on humans are lacking (Smith, 2005).

Recovery is a very important aspect of any physical activity. Among other methods enhancing the recovery, such as active recovery and nutrition, application of cold is gaining on popularity. Application of cold is shown to decrease tissue temperature, thus stimulating the skin vasoconstriction. Presumably, by consequently slowing the metabolism, the swelling and inflammation are alleviated and thereby the degree of injury is limited (Wilcock *et al.*, 2006a, b). Furthermore, the application of cooling also decreases the rate of neural impulse information. This results in reduced level of pain and reduction in muscle spasm (Wilcock *et al.*, 2006a, b). Cold-water immersion is generally performed at water temperatures lower than 15 °C which is based on the temperature where pain begins (Bleakley & Davison, 2009). The water immersions usually take between 10 - 20 min with whole body being immersed (Wilcock *et al.*, 2006b). As suggested by Bleakley and Davison (2009) the physiological and biochemical rationale for using cold-water immersion in sports recovery, however, remains unclear. Further work is needed to clarify the temperature of the water and the duration of cold-water immersion that enhance the recovery.

It can be concluded that the cooling after the exercise is used to alleviate heat strain or to enhance the recovery. Opposed to the first application, where positive effects are well documented, application of cold for sports recovery is mainly based on anecdotal guidelines.

2.3 Thermal evaluation of personal cooling-systems

Thermal effects, such as cooling power and thermophysiological responses initiated upon application of a personal cooling-system can be assessed with human participants, thermal manikins and a thermophysiological human simulator. The use of thermal manikins became popular since the assessment of thermal effects in humans might be biased by the metabolic rate, the body composition and the acclimatisation (Cao *et al.,* 2005). Furthermore, human subject studies are time consuming and safety reasons can limit its realization.

Thermal manikins provide a rapid, accurate and reproducible simulation of dry heat loss from the body and distribution of heat flow over the body (Anttonen *et al.*, 2004;

Holmer, 2004; Meinander *et al.*, 2004; Wyon, 1989). Advanced thermal manikins are constructed to resemble human body (male's, female's or baby's). They consist of independently controlled segments, where generally at least 15 such segments will compose the manikin (Psikuta, 2009). Today's thermal manikins are also equipped with joints enabling the manikin to take positions such as sitting. Additional mechanical drives enable motion such as walking and running. In an effort to simulate human's thermophysiological responses today's thermal manikins are also equipped with sweating nozzles. These attributes suggest that thermal manikins are a valid method to assess the thermal effects of personal cooling-systems.

The literature (Jette *et al.*, 2004; Dionne *et al.*, 2003a, b; Teal, 1996) suggests that thermal manikins are often in use to assess the cooling properties of personal cooling-systems. The cooling-systems that have been assessed with the thermal manikins commonly base on circulating liquid (water). In such systems the cooling properties depends on the flow rate, the temperature of the circulating water and the tube density. Dionne *et al.* (2003a) showed that the heat removal rate vary with the inlet temperature, whereas a plateau is observed when the heat removal rate is investigated as a function of a flow rate. Furthermore, the same group (Dionne *et al.*, 2003b) also showed that for the same flow rate and circulating liquid temperature, the heat removal rates will increase with the density of tubing. Since not all the manikins are able to simulate sweating, personal cooling-systems are being assessed with or without sweating. Dionne *et al.* (2003a) showed that much higher heat removal rates are observed with a sweating manikin. This was ascribed to higher water conductivity compared to that of air layer at the surface of the manikin. Furthermore, Jette *et al.* (2004) showed that the performance of liquid cooling garments is dependent on the surface temperature of the thermal manikin. Namely, the higher the surface temperature, the higher is the heat removal rate. The literature mentioned indicates that in order to compare the performance of various personal cooling-systems, the assessment should follow a standardized procedure, such as that published by the American Society for Testing and Materials (2005). According to this standard a personal cooling-system should be evaluated in climatic chamber with an air temperature of 35 °C and 40% relative humidity, using a sweating thermal manikin with a mean surface temperature of 35 °C.

Although thermal manikins have been greatly improved in the last decade, they are however not adequately simulating thermophysiological responses of humans. Simulation of such response is in particular important when assessing personal cooling-systems due to skin vasoconstriction an associated decrease in heat transfer between the cooling-systems and the body (Cheuvront *et al.*, 2003). Therefore, the cooling power measured using the thermal manikin with a constant surface temperature is characteristic only for this particular surface temperature, and is likely to be higher than the cooling power obtained in human trials for the same cooling-system. To overcome this deficiency a thermal manikin can be coupled with a model of human thermal physiology (thermophysiological human simulator). In the thermophysiological simulator, the thermal manikin is set-up to produce a homogeneous surface temperature and sweat rate over the entire surface of the manikin, which is physiologically changing in time. The area-weighted averages of the skin temperature and sweat rate predicted by the thermophysiological model are used as input parameters to the manikin control system. After certain time intervals, the manikin measures the heat flux released to the environment for the given activity, environmental conditions and clothing worn, and provides it as a feedback for the thermophysiological model. Forerunners of such systems have been initially developed for the automotive industry (Farrington *et al.*, 2004).

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