Thermoregulation in endurance sport and the influence of clothing in heat transfer.

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Introduction

At rest the human body will regulate its temperature to around 37 degrees Celsius. Even at rest this temperature will fluctuate due to our natural circadian rhythms. When activity is introduced our body temperature obviously increases. With moderate exercise this will see our temperature increase to 38 deg, and during intense exercise even up to 40 deg. To regulate our body temperature we have the natural physiological reactions of sweating and shivering, and the voluntary reactions seeking shelter or crawling up into a ball. Another additional voluntary response is the use of clothing. When simplified, we take off clothing when we are hot and we put more on when we are cold. Inherently, we are altering our insulation and therefore heat exchange between the skin and the environment. This process becomes more detailed when the clothing is broken down into materials used and even the construction of individual fibers. The aim of this paper is to identify the role of these individual elements and how they can be used in performance clothing.

Background

Thermoregulation

In order to understand the process of heat exchange between the skin and the environment we have to look at the individual components that make up this process. The amount of heat in the body (storage) can be expressed through this equation:

Storage = Heat production – Heat Loss

Heat production is the difference between our baseline metabolic rate and our metabolic rate during an activity (external work). For heat loss the equation is a little more complicated. Heat loss is the sum of heat exchange via conduction, radiation, convection, evaporation, and respiration. Therefore when the equation is expanded:

Storage = (Metabolic Rate – External Work) – (Conduction + Radiation + Convection + Evaporation + Respiration), or

S = M – (+-W) – (+- E) – (+-K) – (+-C)-(+-R)-(+-RES) (W/m2)

- S = Rate of storage of heat (+ve increase in body heat, -ve decrease in body heat)
- M = Rate of metabolic heat production (METS, 1 met = 58.1 W/m2)
- W = Rate of work (+ve = external work being done, -ve = work absorbed by body)
- E = rate of evaporative heat transfer (+ve is transfer to environment, -ve is transfer to skin)
    - Sweating
- K = rate of conductive heat exchange (+ve transfer to environment, -ve transfer to skin)
    - Heat transfer when in contact with an object (i.e. water , ? supine positions)
- C = rate of convective heat transfer (+ve transfer to the environment, -ve transfer to the skin
    - Air flow around skin – transfer of heat from skin to air (or in really hot cases, transfer from air to skin)
- R = rate of radiation heat transfer (+ve transfer to the environment, -ve transfer to skin)
    - Difference between body surface temperature and temperature of objects in the environment.

- When in sun, radiation occurs from objects to skin

- RES = rate of respiration heat exchange

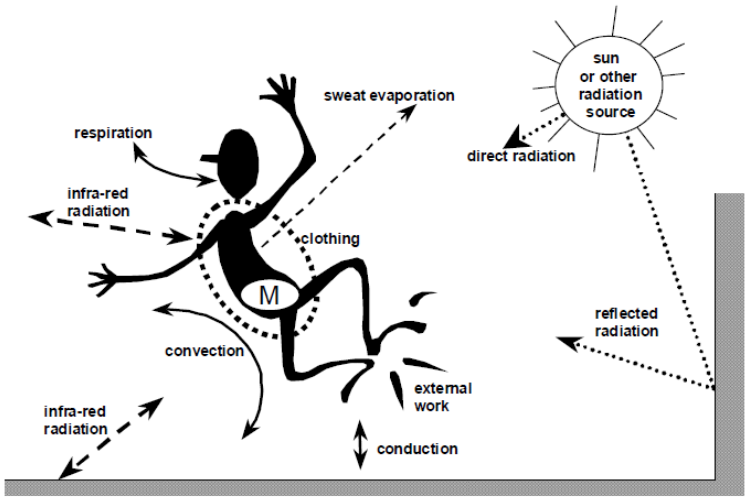


Figure 1. Schematic of thermoregulation during exercise.

Relevant Factors to Heat Exchange

The heat exchange equation listed above is dependent on a number of factors outside of the variable mentioned in the equation. These factors can be deemed as possible resistance to the heat loss aspect of the heat balance equation.

Air Temperature: An increase in air temperature will decrease the benefit of conduction, convection, radiation, and therefore increase reliance on evaporation. A decrease in air temperature will increase reliance on conduction, convection, radiation with a decrease reliance on evaporation.

Air Humidity: More complex than it seems. Moisture concentration is the main factor. Normally moisture concentration will be higher at skin than the environment, therefore causing rate of evaporation to be positive (i.e. skin to environment). In regions of high moisture concentration, not necessarily high relative humidity, this is reversed (environment to skin, -ve rate of evaporation). When 100% humidity is present, moisture concentration will be higher in higher temperatures as apposed to lower temperature.

Wind speed: Increase wind speed across skin will cause an increase convective and evaporative heat losses. If win speed is minimal or non-existent, then visa versa.

Clothing insulation: clothing acts as a barrier between the transfer of heat and moisture between skin and the environment. This process is discussed in more detail below.

Clothing and Heat Balance

As has been suggested, the application of clothing will instantly alter heat exchange between the skin and the environment due to it acting as a layer of insulation. Properties and construction of the materials used in the clothing will significantly alter the insulation and therefore heat exchange ability of the material.

Fiber Thickness

Reducing material thickness has been highlighted as having the largest resistance to heat loss. Therefore, clothing design should look at fibers and materials of least thickness.

Synthetic versus Natural Fibers

The use of synthetic (polyester), natural (cotton), or a combination of both in construction is an area with conflicting research and understanding. Polyester in raw form is a material that does not absorb water. Theoretically, during exercise sweat will accumulate and be trapped on the skin due to its hydrophobic properties. Cotton on the other hand will absorb water instantly due to its water-loving or hydrophilic properties. The use of synthetic and natural fibers in clothing manufacture should also consider the role of skin wetedness on thermoregulation. Nadel and Stolwijk (1973) found that skin wetedness suppressed sweat gland response. It has to be stated that regardless of the material used or the construction of the garment, the addition of any layers of clothing will add a layer of insulation to heat exchange.

Fiber Construction

To make the selection of synthetic versus natural even more complex, whilst cotton absorbs water easily, it does not dry easily, preventing the efficient evaporation of sweat. For this reason, clothing manufacturers have altered the use of polyester in various ways. A combination of synthetic and natural fabrics can help in absorbing moisture from the skin and allowing evaporation to the environment. An example of this is Dryrelease. Polyester with sufficient pores, thin and tubular in design, will allow for moisture to be wicked and dried very quickly. An example of this is Coolmax. Gavin (2000) and Xiangui (2010) made the obvious yet crucial conclusion that a mesh construction improved heat and moisture transfer, especially when applied to regions of greatest sweat evaporation.

Fiber coatings, membranes and other fiber technologies

One of the most exciting but poorly understood areas to enhance heat transfer is the use of fiber technologies. These include hydrophobic and hydrophilic treatments and phase-change material coatings. Ha et al (2010) studied effect of moisture absorption by clothing on thermal responses. Hydrophilic rather than hydrophobic fabrics had better thermoregulatory benefits when comparative testing cotton and polyester. Kwon et al (1995) found hydrophilic properties of fabrics had better thermoregulatory benefits during exercise and rest, especially when influenced by wind.

Clothing Ensembles

Minimizing the layers of fibers, or even more obviously, the layers in the garment has a significant impact on heat exchange.. Each layer has a still air layer attached to outer surface. Therefore, total insulation will be insulation of fabric plus air plus fabric plus air, so forth. The insulation is not just the addition of each layer.

Color

This paper has not looked into the use of color and the effect on thermoregulation in great depth. However it is highly published that white reflects more radiant heat than black, and as a result, less heat is absorbed by the body.

The conclusions of current literature are summarized in table 1.

Table 1. Material variables influencing thermal insulation and therefore heat exchange	
1. Thickness	• Reduced fiber thickness improves heat exchange from skin to environment.
2. Synthetic versus Natural Fibers	• Natural fibers (cotton) are hydrophilic and absorb more moisture and are often more comfortable. However, they evaporation of water is slow. • Synthetic fibers (polyester) are hydrophobic and repel water. This can act as a barrier to heat exchange
3. Construction	• Construction of polyester, and its possible use with cotton can improve wicking and evaporation. • Fishnet / mesh construction offers greater heat dissipation, especially when applied to appropriate region.
4. Coatings, membranes, treatments etc (Hydrophilic, Hydrophobic)	• Includes hydrophobic/hydrophilic treatments and Phase-Change Material coatings • Hydrophilic versus hydrophobic treatments have greater thermoregulatory responses. • Phase-change material coating improve comfort of individual.
5. Clothing ensembles	• Minimizing layers of fiber and the layers in the garment.
6. Color	• White reflects more radiant heat than black
7. Wind and movement	

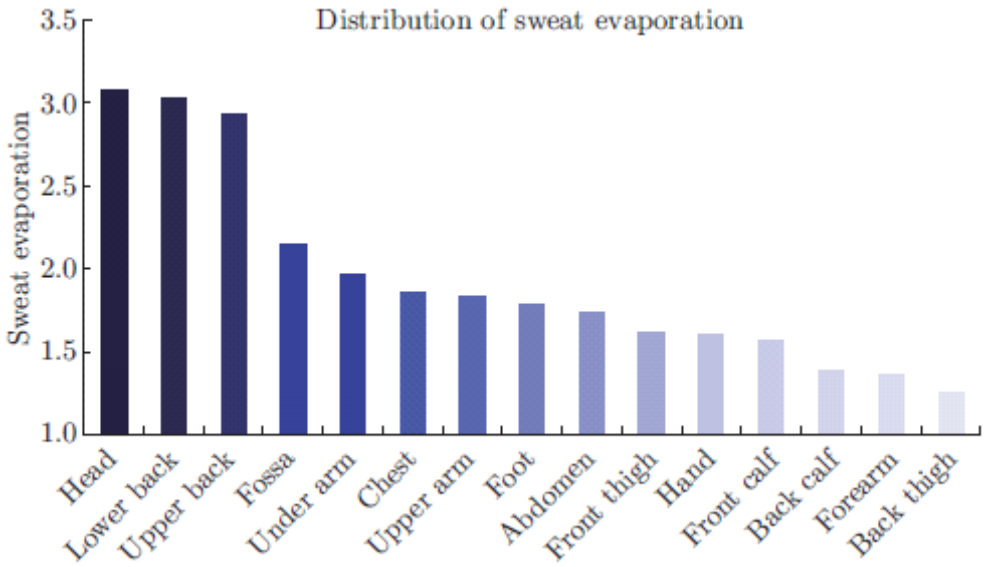
Heat and Sweat Zones

With the knowledge of basic thermoregulation principles and the factors that act as resistance to this process, it is now important to understand the physiological response to exercise, and in particular the heat and sweat zones that occur. Ultimately, combining knowledge of both thermoregulation and heat and sweat zones is paramount in the design and construction of garments.

Distribution of Sweating Evaporation

As mentioned above, when an athlete is participating in hot conditions the primary mechanism of heat dissipation is through sweat evaporation. At rest, 25 percent of daily heat dissipation comes from evaporation as apposed to 80 percent during prolonged exercise. There is a much publicized “shunting” effect during intense exercise where the body redirects blood flow from less vital organs to the muscles required during activity. However, the need for the body to cool itself eventually becomes the most important objective as duration of exercise increases. Here the cutaneous vessels (located in skin) vasodilate to move warm blood from the core to the skin to improve heat transfer.

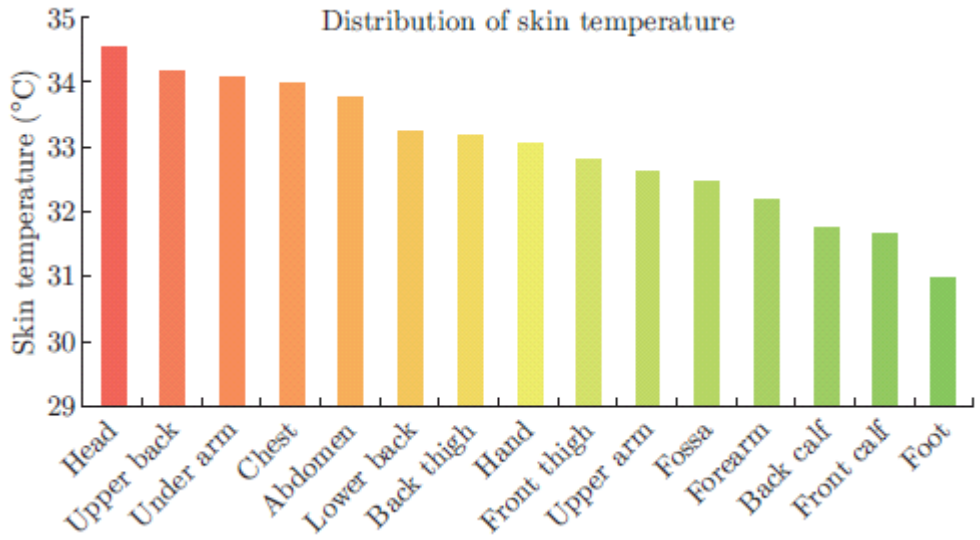
In a search of current literature, 13 papers reported quantitative data of sweat evaporation. Three main protocols were used: 1) exercise for 20 – 60 minutes at moderate intensity in neutral conditions, 2) incremental exercise from low to high work load, 3) resting for 60 minutes with passive heating. The main method of data collection was via sweat capsules. Regions of highest evaporation can be summarized in three areas; 1) forehead and lower and upper back, 2) fossa, under arm, upper arm, chest, foot, and abdomen, and 3) front/back thigh, hand, front/back calf. These results are shown in Figure 2.



The main reasons for sweat evaporation are the proximity of the body part to the body's core organs. The head is a good example of this, as well as its high sudomotor activity. Conversely, body parts such as the calf and thigh are further away from the core and have less sudomotor activity.

Distribution of Skin Temperature

The distribution of skin temperature during exercise was reported in 22 publications. The protocols used in these publications can be summarized in four ways; 1) resting then exercising for 20 – 60 minutes in low to moderate intensities in neutral/hot conditions, 2) incremental exercise from low to high work load, 3) resting for 60 minutes with passive heating, 4) mannequin test with set work load. The testing methods used included; 1) infrared color thermograph, 2) thermistor with probe thermocouple attached directly on the skin, and 3) CAD computer simulation. The results are similar to those shown in the distribution of sweat evaporation, except they can now be devided into five categories; 1) Head, 2) upper/lower back, under arm, chest, and abdomen, 3) thigh and arm, 4) hand, forearm, and calf, and 5) feet. These results are shown in figure 3.



Results of infared thermograph are a good visual representation on the distribution of skin temperature. Merla et al. in 2010 looked at cuntaneous temperature in 15 runners as they ran on a treadmill until maximum heart rate was reached. These results are shown in figure 4.

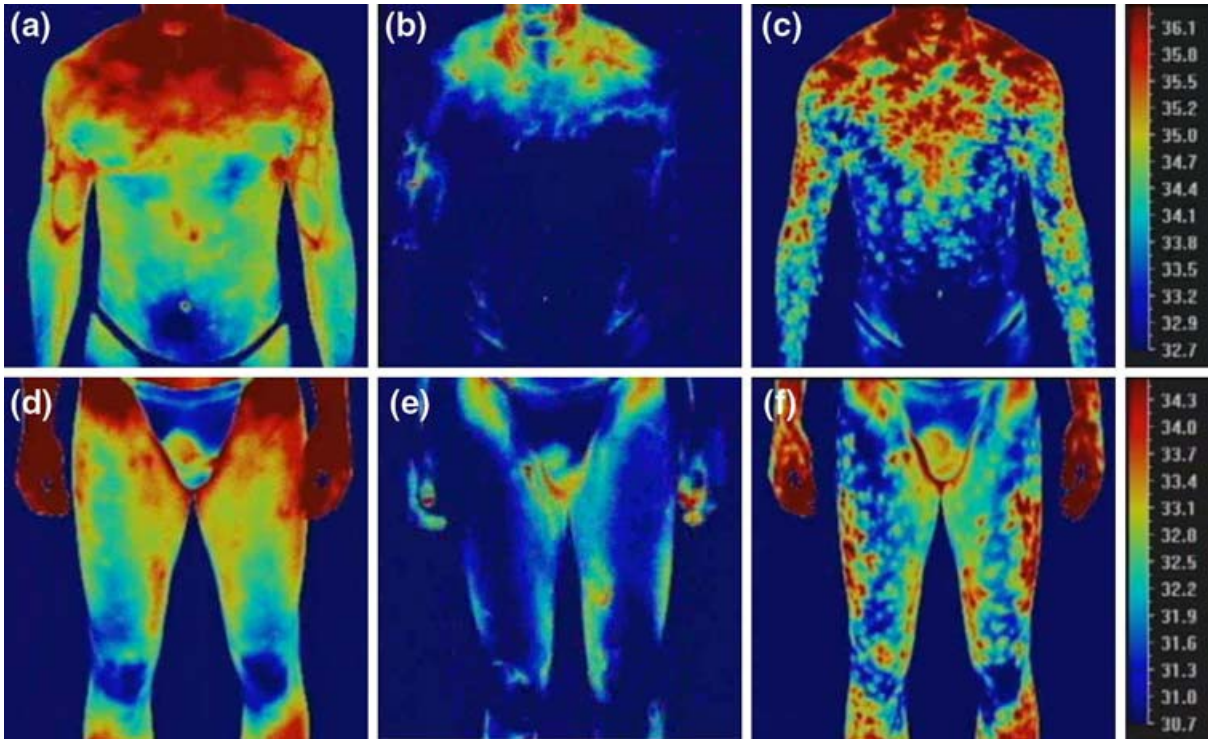


Figure 3 shows an individual during rest (a, d), immediately after reaching maximum heart rate (b, e), and during recovery (c, f). These images show the movement of blood to vital organs during intense exercise, and then the process of vasodilatation of cutaneous blood vessels to dissipate heat during recovery or during prolonged exercise.

Areas of future research and testing

To best utilize the areas of knowledge outlined in this paper, it is important to plan for future testing. This can be performed on individual material or completed garments. As a result of this paper, areas

of research into the materials and construction method mentioned should include thermoregulatory and athlete subjective testing.

Thermoregulatory testing that should be completed includes:

- Thermal insulation of clothing (see ASTM F1291 standards)
    - Using manikin
    - Static versus Dynamic measuring
- Evaporative heat exchange (see ASTM F2370 Standards)
    - Using mannequin
    - Permeation indices
    - Evaporative resistance
- Moisture Management
    - TM195-TM 195 Liquid Moisture Management Properties of Textile Fabrics Standards
- Comparative testing of industry-leading garments using the above tests
- Use of hats

Due to the complexity of materials, their construction, and the minimal research that currently exists, it will be important to observe the comfort and performance of the people that will wear these garments. Areas to be tested on individuals should include:

- Skin temperature mapping
- Evaporative (sweat) loss / skin wetedness
    - Temperature sensors determining rate of cooling for wet skin, or tactile sensors
- Subjective reporting (e.g. constriction,
    - See article “The effect of clothing ventilation openings on thermoregulatory responses during exercise”
- Comparative testing of industry-leading garments using the above tests

Conclusion and relevance to future clothing development

This paper highlights the complexity of thermoregulation during exercise, and further, during endurance exercise. The heat balance equation consists of two components, heat production and heat loss. The production of heat is difficult to alter due to metabolism and work rate playing a large role. However, reducing radiation and conduction from close object will help decrease heat production. The mechanisms of heat loss through conduction, radiation, convection, evaporation, and respiration are variable to environment (air temperature, humidity, wind speed) and the objects on (clothing) and around (surfaces, etc) the person.

In literature outlined the role of clothing in heat loss is significant. The addition of clothing instantly adds a layer of insulation. Therefore, the process of dissipating heat whilst also keeping the person comfortable is the task of clothing manufacturers. Reducing the thickness of material used is of paramount importance. It is an obvious note here that the resulting opaqueness of the material has to be taken into consideration. The use of synthetic and natural fibers is difficult to come to a definite conclusion as the author has not found any literature based on industry-wide standards for rating moisture management. The use of polyester with altered construction such as tubular fibers,

tunneling, meshing, or the addition of cotton can improve heat and moisture transfer. Furthermore, this paper shows that polyester treated with a hydrophilic substance will also improve heat and moisture transfer. It is important to note that evidence currently suggests that skin wetedness helps suppress sweat gland response and therefore the risk of heat stress. Therefore there exists a complex relationship between moisture wicking and evaporation, and maintaining adequate fluid-balance and comfort. There needs to be future research into all the variables mentioned in this paper, using industry moisture-management rating standards, as well as evaluating the subjective response of the person's comfort wearing the garment.

The emphasis on materials and their construction in this paper is a crucial step is the design and production of clothing. However, it is of equal importance to then take into consideration where these materials and their various connotations in construction can be used on different areas of the body that observe differing temperature and evaporative levels. During prolonged exercise, regions close to the trunk, in particular the head, back and underarm have the highest skin evaporation levels, whilst the calf, forearm, and thigh have the least. These same observations are similar for skin temperature. With this in mind, clothing manufacturers should target these specific areas with the material and construction techniques mentioned to best optimize heat transfer.

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