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Thermal Physiology and Local Responses of Human Body During Exercise in Hot Conditions

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Abstract

Body temperature is maintained by effective thermoregulation, which depends on heat balance that includes heat production and heat loss. Skin moisture and water evaporation from the body play an important role in heat transfer, especially during exercising or in hot conditions. The regional skin evaporation can significantly affect the heat release of the each body part, the pattern of skin temperature distribution and the thermoregulation. Indeed, the distribution of sweat evaporation and skin temperature can also be applied as a means of managing the body thermoregulation. This study reviews the thermoregulation of human body, local skin evaporation and the skin temperature distribution. It also highlights the implication of local skin evaporation and skin temperature in the development of sportswear and the prevention of heat disorder in hot conditions.

Keywords: Heat Balance; Thermoregulation; Regional Sweat Evaporation; Regional Skin Temperature

1 Introduction

The body temperature is maintained by effective thermoregulation, which balances the interaction of air, clothing and skin temperature via the process of heat production and heat loss. In hot conditions, the rate of heat loss by convection and radiation decreases due to a decrease in the gradient of skin-to-environment temperature. However, the skin evaporation increases which contributes about 80% of total heat release of the body [1, 2]. Skin evaporation is regarded as the primary mechanism which affects thermoregulation in hot conditions. Due to the differences between sweat gland density and sensitivity of the body, the skin surface has non-uniform sweat evaporation on each part of the body. Meanwhile, distribution of skin temperature is not constant because of the variation of anatomic structures and tissue thickness as well as the distribution of blood flow. During the past five decades, the skin temperature and evaporation distribution of human body has been investigated by several research groups. Despite different applied research

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protocols and measurement methods, the skin temperature and evaporation mapping patterns have not been systematically highlighted. It is necessary to analytically summarize sweat evaporation distribution and the mapping pattern of skin temperature, because of their effects on thermoregulation, as well as the potential benefits on the development of functional sportswear.

This study presents the findings from the literature of the heat balance of human body and the mechanism of thermoregulation. The details of the distribution of sweat evaporation and regional skin temperature as well as the summary of the mapping pattern of human body are also presented. After that, the interaction between the local skin evaporation and skin temperature are discussed. Based on the researches reviewed, the implication of skin temperature and evaporation are generally explored in the development of sportswear and prevention of heat disorder.

The framework of this review is illustrated in Fig. 1.

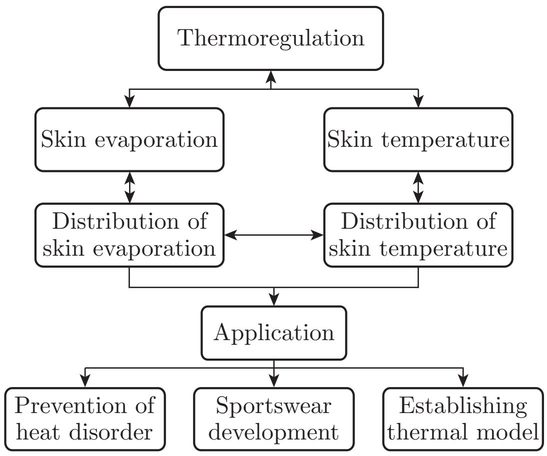

Fig. 1: Framework of this paper

2 Heat Balance and Thermoregulation

Normally, the core temperature of a healthy adult human is 36.8 ± 0.4℃ [3, 4]. The heat balance of the human body can be expressed as equation 1 [1, 2, 5, 6]

$$S = M - (\pm W) - (\pm E) - (\pm K) - (\pm C) - (\pm R)(W/m^2)$$

where:

S is the rate of storage of heat (positive = increase in body heat content, negative= decrease in body heat content);

M is the rate of metabolic heat production (always positive in a living animal, during rest, M = metabolic heat production);

W is the rate of work (positive = external work accomplished, negative = mechanical work absorbed by the body);

E is the rate of evaporative heat transfer (positive = evaporative heat loss, negative = evaporative heat gain);

C is the rate of convective heat transfer (positive = transfer to the environment, negative = transfer into the body);

K is the rate of conductive heat transfer (positive = transfer to the environment, negative = transfer into the body);

R is the rate of radiant heat transfer (positive = transfer to the environment, negative = transfer into the body).

The thermoregulation of human body has been studied for over two hundred years, but the mechanisms are still under investigation. To date, it is well recognized that the human thermal regulation is controlled by human skin, muscle and a part of the brain called hypothalamus. Meanwhile, the nervous system is also involved [5, 7, 8, 9]. The thermoregulation of human body is summarized in Fig. 2.

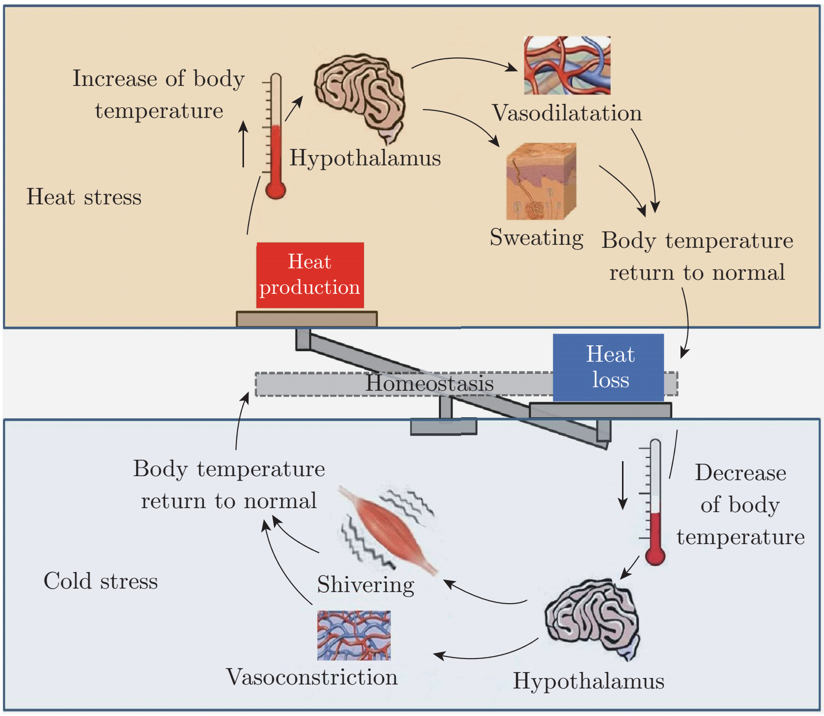

Fig. 2: Thermoregulation of human body

The signal of temperature regulation is collected from receptors in both skin and core of the body. Stimulations from environmental temperature are primarily detected by thermal receptors located in the skin. It is transmitted as nerve impulses to the hypothalamus. Then it initiates the appropriate response in an effort to maintain the temperature around the set-point [5].

Under heat stress, a significant amount of peripheral tissue can be involved to increase blood flow and vasodilatation, in order to help heat transfer from body core to skin surface and ambient environment [5]. Further, the hypothalamus initiates sweating by stimulating sweat glands to increase heat loss from the skin. In these situations, heat loss by evaporative cooling increases. When environmental temperature is higher than the body core temperature, sweat evaporation is the only physiological way of human body to lose heat [8, 9].

Under cold stress, vasoconstriction of skin can eliminate cutaneous blood flow to reduce heat convective, conductive and radiant losses. In this situation, the subcutaneous fat and musculature provide an insulated layer [5]. Moreover, the muscle begins to shiver in order to increase heat production.

3 Distribution of Sweating Evaporation

Sweat evaporation is the primary mechanism of heat dissipation in hot conditions. It is the process by which water molecules are transferred from core to skin and converted to water vapor, taking the heat away from the body. Every gram of water evaporation will absorb 580Kcal (2427Kj) of heat [5]. At rest, it accounts for approximately 25% of daily heat dissipation, but during exercise, it will increase to 80% of the heat loss [1, 2]. The amount of sweat evaporated from skin is dependent upon the area of wet skin for heat exchange, vapour pressure gradient and natural convective currents [7]. The maximum sweat rate of humans is 10 to 15 g/min/m^2. The sweat evaporation is found to vary widely among different individuals [10, 11], sexes [12, 13], ages [14, 15] and nations [16, 17]. In order to make a systematic review, research has been conducted using keywords 'sweat gland', 'sweat gland distribution', 'skin evaporation', 'sweat rate distribution' and 'regional sweat rate' in databases, such as 'Science', 'Pubmed', 'Google academic' and 'Scifinder'. A total of thirty papers were found, which were published from 1945 to 2011. Among them, thirteen papers reported quantitative data of sweat evaporation in regional body parts. These studies were conducted by different protocols and applied different measurement methods. The protocol used in those papers can be summarized into three aspects: (1) exercise for 20-60 minutes in moderate intensities in neutral conditions [18], (2) incremental exercise from low to high work load [19, 20], (3) resting for 60 minutes with passive heating [16, 17]. The measurements applied in the studies of regional skin evaporation include the following: (1) Using absorbent technique/pads and determining gravimetrically the mass of technique/pads with sweat [12, 18, 21]; (2) Attaching ventilated sweat capsules directly on the skin [22]; and (3) Directly measuring water evaporation from skin surface [23-25]. The predominant method for sweat capsules measurement can only measure a small number of sample sites using a relatively limited surface area (3-12 cm^2). The regional sweat data is generalized from only <2% of the body area. Compared to the predominant method of sweat capsules, the absorbent technique is a reformative method in that the regional body is fully covered by absorbent pad. When the regional body is fully covered, the sweat rate of the body part can be measured directly. However, it is unknown whether the absorbent technique with plastic stretch clothing/socks will lead to excess sweating of nude body or not.

Six studies were selected because of their accurate research design and high citation index. They had varied protocols and measurements of sweat evaporation, which are summarized in Table 1. Table 2 demonstrates the sweat evaporation in each body parts from previous studies.

Data presented in Table 2 are standardized and then treated by Fractional ranking [26]. After ranking, the sweat evaporation in each part is summarized in Fig. 3. The values of skin temperature in each part can be divided into three levels. The highest level is presented by forehead and the lower and upper back, which are consistently found in some other studies as well [18, 19, 21]. The second level is presented by fossa, under arm, upper arm, chest, foot and abdomen, which are mainly located in upper body, with the exception of feet [25]. And the third level is presented by front/back thigh, hand, front/back calf, where major parts are located in the lower body [12, 18, 19]. The head, representing the highest sweat evaporation, may be explained by its highest sudomotor sensitivity of the body and close distance with the core body part. The second highest levels of sweat evaporation are located at the back which may be due to the highest temperature of the organs in the trunk. Similarity, the arms and thighs, with the third highest level of skin temperature, have dynamic muscles which produce abundant heat. It has been proved that when higher heat simulation is accepted, the temperature gradient may be initiated faster, which results in more sweat evaporation [5, 7]. The other body parts such as hand, calf, and feet are all

Table 1: Summary of the protocols and measurement methods of sweat evaporation

Researches	[18]		[12]	[25]			[21]	[19]	[22]
Temperature (℃), RH (%), Air velocity (m/s)	25 ℃, 50%, 2 m/s		25 ℃, 53%, 2 m/s	28 ℃, 55%, < 0.5 m/s			20 ℃, 50%, < 0.5 m/s	36.6 ℃, 46%, < 0.5 m/s	36.6 ℃, 60%, < 0.5 m/s
Subjects	9 M	9 M	9 M, 9F	10 M	10 M	10 M	10 M	6 M	10 M
Exercise Intensity	55% VO2max	75% VO2max	65% VO2max	Resting	40% VO2max	60% VO2max	45% peak power	40% peak power	Incensement from 50W
Duration (min)	60	60	60	20	20	20	90	40	N/A
Test Method	A	A	A	B	B	B	C	C	D

Note: A: Sweat absorbent pads, which were attached to custom-made plastic sheeting for fast application to the body and to prevent the evaporation of sweat during the test periods; B: Directly measure water evaporation from skin surface; C (similar to A): Sweat patches consisted of parafilm being attached to the skin with a wound dressing. Regional sweat rates were determined gravimetrically by the change in mass of the aspirating syringe; D: Ventilated sweat capsules attached to skin. [M for Male; F for Female].

Table 2: Summary of sweat evaporation in each body part, $g/(m^2h)$

Researches		[18]		[12]	[25]			[21]	[19]	[22]
Body Parts	Head	894±708	2057±900		14±6	27±15	58±24	1434±744	1632±198	
	Chest	324±148	606±262	564±178	14±7	26±10	50±10	570±324	888±96	1050±186
	Abdomen	383±170	658±267	715±248	12±4	28±11	49±7	390±162	852±96	846±144
	Under arm	145±81	258±90	245±112	17±4	57±18	60±9	312±150	1260±84	1122±168
	Upper arm	322±109	620±202	540±187	19±9	33±11	55±8	570±276	876±108	1152±204
	Forearm	238±140	359±80		15±9	25±8	51±6	450±240	906±120	
	Hand	98±58	126±53		24±10	38±2	50±9	546±456	1098±156	
	Upper back	710±246	1062±360	845±326	18±8	30±9	66±3			
	Lower back	797±250	1139±364	1024±287	16±8	34±10	60±5	510±246	834±54	
	Front thigh	280±103	390±128		15±7	29±4	56±7	396±174	570±120	
	Front calf	355±210	441±218		13±8	28±8	54±10	456±162	834±204	
	Back thigh	209±56	274±79		10±3	24±5	53±12			
	Fossa				17±7	42±13	60±15			
	Back calf	256±105	338±133		11±2	30±4	51±10			
	Foot	202±95	225±84		43±13	34±14	41±10	336±138		

segments that have long distances from the core of the body and exhibit a small area of skin for evaporation. This will explain the reason why they present the lowest level of sweat evaporation.

4 Distribution of Skin Temperature

Among the previous literature, twenty two publications reported the distribution of skin temperature. These studies were naturally conducted by different protocols and test methods. The

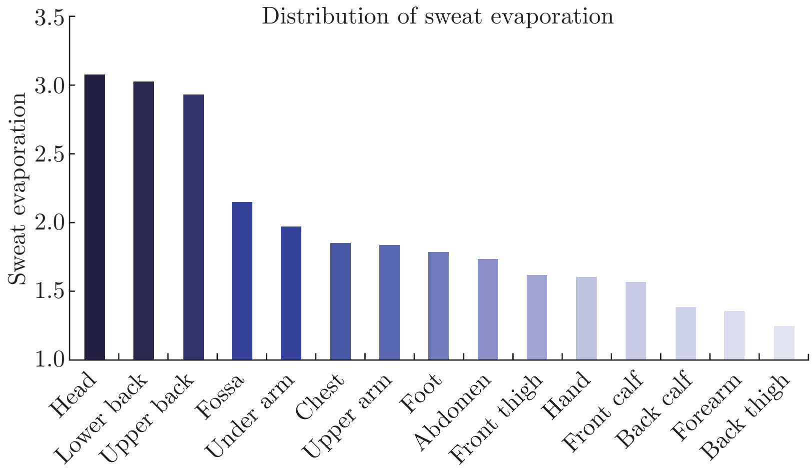

Fig. 3: Summary of sweat evaporation in each part

protocol used can be summarized into four ways: (1) resting for a period and exercising for 20-60 minutes in low to moderate intensities in neutral/hot conditions [18, 25], (2) incremental exercise from low to high work load [22], (3) resting for 60 minutes with passive heating [16], (4) manikin test with set work load [27]. The test methods are: (1) Using Infra-red color thermograph to visualize temperature of skin surface [28]; (2) thermistor with probe thermocouple attached directly on the skin [17, 22, 25]; (3) CAD computer simulation [27]. Infra-red color thermograph is a method being used for many years, by which skin temperature can be visualized as direct mapping. However, the skin temperature cannot be obtained if the skin is covered by clothing. Using thermistor to measure skin temperature on each body site is again an accurate method. However, when it is used, more attention needs to be paid to ensure that the sensors remain in good contact with the skin. Otherwise, the results of measurement on the exercising subjects will be biased by the ambient temperature [29, 30]. CAD computer simulation is a method using computer software packages for demonstrating the thermal response of human body. The advantage of this method is that the experiment will not be limited by environmental conditions and human subjects.

Based on the above analysis, five studies were selected to analyze and summarize the mapping pattern of skin temperature distribution in this study. The protocols and the measurement methods of skin temperature from the selected publications are presented in Table 3. Table 4

Table 3: Summary of the protocols and measurement methods of skin temperature

Researches	[22]	[25]			[27]	[32]				[17]	
Temperature (℃),	36.6	28			22	21	24	26	29	28	
RH (%)	60	55			45					50	
Air (m/s)	< 0.5	< 0.5			0.14	0.05	0.05	0.05	0.05	< 0.5	
Subjects	10 M	10 M	10 M	10 M	Manikin	12 M	12 M	12 M	12 M	10 M	10 M
Exercise Intensity	Incensement	Rest	40% VO2max	60% VO2max	100 W/m^2	Rest	Rest	Rest	Rest	Passive heating	
Duration (min)	N/A	20	20	20	N/A					60	
Test Method	T	T	T	T	CAD	T	T	T	T	T	T

Note: T for thermistor with probe thermocouple attached. [M for Male; F for Female]

Table 4: Summary of skin temperature in each body part (℃)

Researches		[22]	[25]			[27]	[32]				[17]	
Body Part	Head		33.9±0.7	33.6±1	33.6±1.3	33.9	34.1±0.2	34.9±0.1	35.4±0.1	35.5±0.1	35.1±0.2	35.3±0.2
	Chest	36.6	32.9±1.1	32.5±1.2	31±2.1	35.4	33.4±0.1	34.1±0.2	34.78±0.2	35.1±0.1		
	Abdomen	35.5	32.8±1.1	32.3±1.3	30.6±1.9	35	33.4±0.2	34.0±0.1	34.7±0.2	35.4±0.1		
	Under arm	37	33.7±1.1	33.3±1.1	32.3±1.7							
	Upper arm		32.5±1.1	32.1±1.1	31.6±1.7	36.7	30.3±0.2	31.3±0.2	32.5±0.1	33.9±0.3		
	Forearm		32.5±0.9	33.1±1.1	31.1±1.6		30.3±0.1	31.3±0.1	32.7±0.2	34.1±0.2		
	Hand		33.3±1.1	33.1±1.1	32.3±1.4	33.2	30.3±0.3	31.6±0.3	33.0±0.4	34.2±0.2	34.7±0.1	34.7±0.1
	Upper back	36.6	32.8±1	32.3±1.3	31.6±1.6	35.9	33.4±0.3	34.2±0.1	34.9±0.2	35.7±0.1		
	Lower back	36.8	32.2±1.1	31.6±1.3	30.7±1.8		31.7±0.1	33.8±0.1	33.9±0.1	34.8±0.2		
	Front thigh		33.4±1	32.1±1.1	31.8±1.4	34.6	30.8±0.1	32.2±0.2	33.2±0.1	34.2±0.1		
	Front calf		31.9±0.9	32±1.1	31.6±1.6	32	29.8±0.2	30.9±0.2	32.1±0.2	32.9±0.2		
	Back thigh		32.4±1.1	32.1±1.1	31.6±1.7		32.8±0.1	33.7±0.1	34.6±0.3	35.3±0.1		
	Fossa		32.4±0.9	32.3±1	32.1±1.4		30.9±0.3	32.2±0.3	33.1±0.2	34.1±0.2		
	Back calf		31.5±0.9	32±1	31.7±1.3							
	Foot		32.2±1.2	33.2±1.2	34.1±1	31.1	26.9±0.1	27.9±0.2	30.1±0.2	32.2±0.1		

reveals the summarized data of skin temperatures in each body part.

Fig. 4 illustrates the regional skin temperature distribution. The highest skin temperature is located on the head. The upper/lower back, under arm, chest and abdomen, which are all located on or near the trunk of the body, apparently at the second highest level. The thigh and arm are at the third level, followed by hand, forearm and calf at the fourth level. In fact the feet have significantly lower temperature than all other body parts. The mapping pattern of skin temperature can be explained as the distance between body core and the other body parts, the balance of local heat production and heat loss, as well as the local blood flow [25, 32]. The highest skin temperature appears on or near the trunk part because the trunk is the core of the body in which the organs are proved to have higher temperature. The body parts located at a longer distance from the body core which may have lower skin temperature than that of the trunk. The exception are the hands, which may be due to the abundant capillary vessels and blood flow in hand than that on the forearm, calf and feet [8, 9].

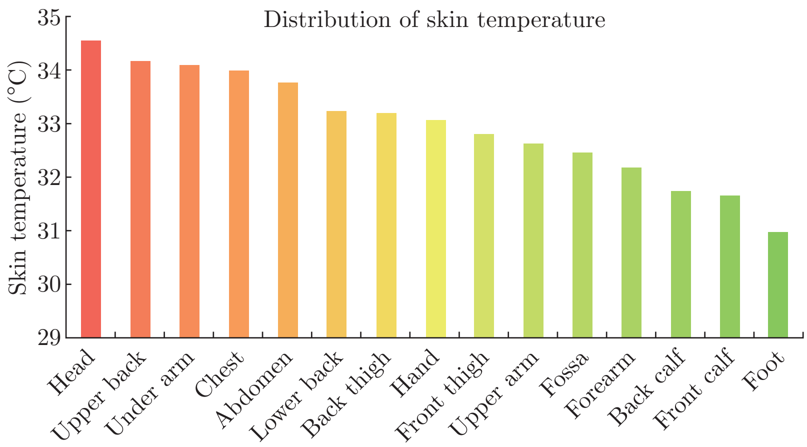

Fig. 4: Summary of skin temperature in each part

5 Interactions between Local Skin Temperature and Skin Evaporation

The local skin temperature is determined by the distance between body core and the other body parts, the balance of local heat production and heat loss, as well as the local blood flow [25, 32]. Under heat stress, blood flow increases to enhance heat release by regional skin evaporation. However, increased periphery blood flow may increase the localized skin temperature. When sweat occurs, the local sweat evaporation will dissipate heat from body surface to the external environment, and the local skin surface temperature will decrease. Regional sweat evaporation can enlarge the localized temperature gradient between body core and skin surface. It also enhances the heat release from body and creates impact on the thermoregulation of the human body.

6 Concluding Remarks

The body temperature is maintained by effective thermoregulation via the process of heat production and heat loss. From this review, it is recognized that local sweat evaporation and skin temperature can affect the thermoregulation of the human body. Regional sweat evaporation and skin temperature creates an impact on heat release and the thermoregulation of the human body. Moreover, varying regional sweat evaporation and skin temperature can be summarized as the mapping pattern of human body.

It is noted that sportswear is the intermediate between human body and external environment, and its capability of releasing heat and water vapor will have a significant impact on the thermal status of athletes. The summarized mapping pattern of skin evaporation and skin temperature may provide references for sportswear design and engineering by maximizing the heat and moisture dissipation capability of sportswear. Finally, it may play an important role to reduce the heat stress of the athletes, and to prevent the risk of heat disorder. However, indeed we need to know much more about how to apply these theoretical issues in producing sportswear and managing thermal stress of athletes in hot conditions.

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