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The intersection-of-asymptotes method applied to the study of skin temperature changes over time during running exercise

Giovanni Tanda

Dipartimento di Ingegneria Meccanica, Energetica, Gestionale e dei Trasporti (DIME), Università degli Studi di Genova, Genova, Italy

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ABSTRACT

The intersection of asymptotes method is used to describe the changes in skin temperature of the human body during running exercise. Skin temperature variations are induced by thermoregulatory mechanisms, which are influenced by both physiological and environmental factors. The aim of this study is to succinctly and comprehensively connect these factors to create an easily interpretable tool for understanding this process. Based on simplified energy balance equations under dynamic conditions for both the early and late stages of exercise, two asymptotic solutions for skin temperature are derived. The point of intersection between these solutions determines the moment at which the transition from skin vasoconstriction to vasodilation occurs. The shapes and the intersection of the two asymptotes enable the inference and interpretation of actual skin temperature variations throughout the course of exercise.

1. Introduction

The human body is governed by the laws of thermodynamics. At rest, it maintains a constant internal body temperature of approximately 37 °C by balancing metabolic heat production with heat losses to the environment. Compared to rest conditions, intense physical activity, such as running exercise, triggers muscular work accompanied by an increased rate of metabolic heat production. This increase is balanced by an increased rate of heat loss, or heat is stored in the body; therefore, steady-state conditions, typically occurring at rest, do not normally exist during exercise. Moreover, physical exertion activates compensatory vasoregulation, causing a reduction in blood flow to the skin (skin vasoconstriction) while increasing blood flow to active muscles. On the other hand, when internal heat accumulation elevates core temperatures excessively, blood flow is redirected to the skin (skin vasodilation) to enhance heat transfer to the environment. Hence, the cardiovascular system faces the challenge during exercise of ensuring maximal blood flow to muscles for metabolic demands while directing adequate blood flow to the skin for thermoregulation [1].

According to the model introduced by Gagge et al. [2], the human body can be represented by two concentric compartments: the core and the skin, which exchange heat through direct contact and the peripheral blood flow (Fig. 1, left-hand diagram). This simple lumped-parameter model considers two representative temperatures: the core temperature T_{cr} and the skin temperature T_{sk}. While the core temperature essentially reflects the temperature of the deep body, regulated by the brain, the skin temperature is primarily influenced by skin blood flow and environmental conditions [3]. In accordance with the circulatory system model depicted in the right-hand diagram of Fig. 1, adapted from Bejan's book [4], at the onset of exercise increased oxygen provision to exercising muscles necessitates a greater demand for blood flow to active muscles, resulting in a reduction of cutaneous blood flow (skin vasoconstriction). As a consequence, if the environmental air temperature is lower than body temperature, a reduction in the skin temperature occurs due to exposure to cooler environment. At the same time, heat begins to accumulate into the body due to the intense metabolic heat production, leading to a rise in core temperature. Beyond a set-point temperature, the hypothalamus activates the heat loss response consisting in cutaneous vasodilation and sweating. This vasodilator response augments blood flow to the skin, and the warmer blood redirected from the internal body to the surface (blood perfusion) enhances convective heat transfer from the core to the periphery, resulting in a rise in skin temperature. The switch from vasoconstriction to vasodilation is also subject-sensitive, as well-trained runners may tolerate relatively high core temperatures or produce relatively low metabolic heat through the oxidation process compared to less trained runners under similar exercise conditions (e.g., at the same running speed). In such circumstances, skin vasodilation may be delayed, or vasodilator stimulus may be significantly mitigated, thereby leaving the blood (and oxygen) supply to active muscles and running performance unaffected. Conversely, a prompt and pronounced cutaneous vasodilation response may adversely affect running performance by reducing the delivery of blood (and oxygen) to exercising muscles.

The interaction between core and skin temperatures depends not only on the physiological characteristics of the subject (such as metabolic heat production and tolerance to high core temperatures) but also on environmental conditions. For instance, high air temperatures and

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Nomenclature

C'	skin-to-ambient conductance [W K^{-1}]
C_{cr}	core thermal capacitance [J K^{-1}]
C_{sk}	skin thermal capacitance [J K^{-1}]
c_b	body specific heat [J kg^{-1} K^{-1}]
c_{bl}	blood specific heat [J kg^{-1} K^{-1}]
K	core-to-skin conductance [W K^{-1}]
K'	core-to-skin conductance including blood perfusion [W K^{-1}]
M	metabolic rate [W]
M_{net}	net metabolic rate [W]
m	body mass [kg]
$\dot{m}_{bl}$	skin blood mass flow rate [kg s^{-1}]
Q_{res}	respiration heat losses [W]
T_a	ambient temperature [°C]
T_{cr}	core temperature [°C]
$T_{cr,0}$	core temperature at exercise onset [°C]
$T_{cr,max}$	maximum core temperature [°C]
T_{sk}	skin temperature [°C]
$T_{sk,0}$	skin temperature at exercise onset [°C]
t	time [s] (expressed in [min] in Fig. 2 and Fig. 5, right-hand side)
t^*	exercise time to cutaneous vasodilation [s]
W	external mechanical power [W]

Greek symbols

α	relative mass of skin

relative humidity levels pose significant challenges to human cardiovascular control and the oxygen supply to exercising muscles due to increased thermoregulatory demand for skin blood flow. While core temperature is expected to increase slightly from its resting value after the onset of exercise, skin temperature can vary considerably (i.e., decrease, increase, or remain steady) depending on the vasoconstriction/dilation mechanisms described previously. Skin temperature changes over time during exercise appear capable of describing physiological adaptations related to exercise type, intensity, and duration. In recent years, experimental studies facilitated by the development of infrared thermography have measured the thermal map of the body surface and its changes during various sports activities, such as biking, running, and rowing [5–12]. Among these studies, those focusing on running exercise typically show a reduction in skin temperature (averaged over the whole or a major part of the body) immediately after exercise onset, followed by a stable plateau, or further slight decreases or increases over time. Fig. 2 illustrates some examples of skin temperature evolutions over time during running exercise extracted from refs. [8, 10]: measured data, averaged among several subjects, reflect a general trend, although variations in individual responses associated with different levels of physical efficiency can be observed [11]. At the end of exercise, the redirection of blood flow to the skin, prompted by the ceased demand from exercising muscles, leads to a rapid increase in skin temperature to re-establish pre-exercise levels. However, as literature studies involve different categories of athletes, levels of physical effort, poorly controlled or non-standardized environmental conditions, and various exercise protocols, the documented skin temperature responses to exercise, often seemingly contradictory, may be difficult to interpret.

The aim of this study is to provide a comprehensive interpretation of skin temperature variations during running exercise across varying intensity and environmental conditions. The approach presented here draws upon the method of intersecting the asymptotes, originally proposed by Bejan [4] as a potential criterion for optimizing engineering systems. As described in ref. [4], the spatial and temporal structures observed in nature emerge from an optimization process subject to global and local constraints. While spatial structure typically involves optimizing geometric forms to facilitate natural flow or engineered flows, the optimization of temporal structure in transient, intermittent, or pulsating flows in nature and engineered systems requires identifying optimal times or frequencies. The intersection of asymptotes method exploits analytical relationships between a dependent variable representing the objective function (e.g., a heat transfer rate to be maximized) and an independent variable to be optimized (e.g., a varying geometry like a channel spacing) at two extremes (e.g., very low and very high spacings). By utilizing these asymptotes, the method identifies

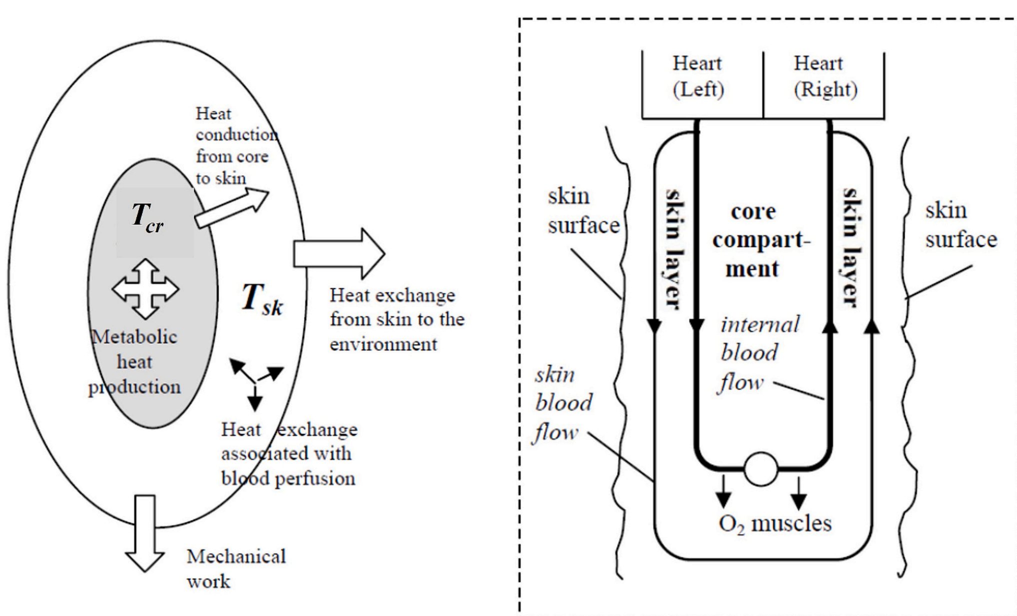

Fig. 1. Two-nodes lumped parameter model (left) and circulatory system with internal and peripheral blood flow (right).

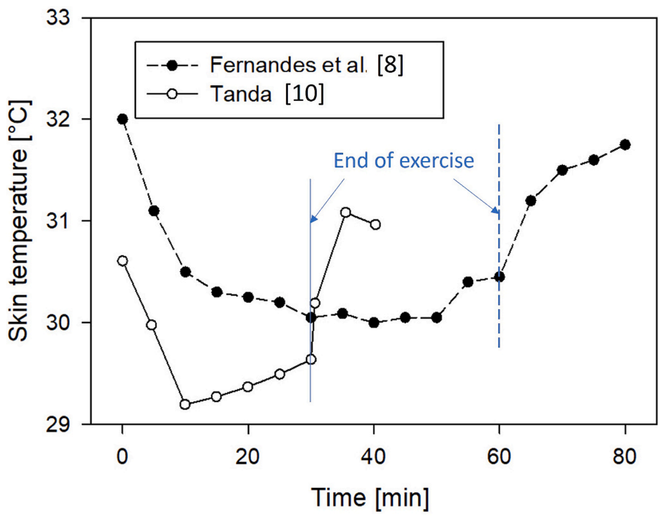

Fig. 2. Skin temperature variations over time for two sample groups (average among 12 subjects, de Andrade Fernandes et al. [8] and 4 subjects, Tanda [10]) running on treadmill at constant load.

conditions (approximately located by intersecting the asymptotes) that optimize the structure or the phenomenon under observation. Intersecting the asymptotes is a central method in constructal theory and design, successfully applied to optimize engineering systems such as: (i) stacks of parallel plates under natural, forced, and mixed convection and (ii) fluid-saturated porous layers heated from below, with the common objective to maximize heat transfer density, and (iii) vascularized solid bodies exposed to intense heat flux from one side and thermally controlled by pumping a coolant from the other side, with the objective of suppressing excessive hot-spots in the material. Additionally, the method has been applied to various physical and biological systems, including: (iv) temperature of a fire as a function of fuel profile, and (v) optimal size of an animal organ, balancing energy expended to comply with irreversibilities against energy spent carrying the organ. These and other applications of the method have been extensively illustrated by Bejan and co-authors in the aforementioned ref. [4] and subsequent books [13–18].

In this work, two different skin temperature changes over time (the asymptotes for the "early" and "late" time periods of exercise), based on a simple lumped-parameter model, are outlined. From the balance of the two competing trends, the possible shape of the real skin temperature time-evolution, and the role played by the main variables on which skin temperature depends, have been highlighted.

2. Materials and methods

According to the two-node lumped-parameter model, the temperatures of each compartment (the core temperature T_{cr} and the skin temperature T_{sk}) are assumed to be uniform and two coupled heat balance equations, in transient conditions, can be derived separately for each compartment. A brief description of the equations involved in the model and the related assumptions is provided, refer to [19] for further details.

The two heat balance equations for the core and skin compartments are

$$C_{cr}\left(\frac{dT_{cr}}{dt}\right) = (M - W) + K(T_{sk} - T_{cr}) + \dot{m}_{bl}\, c_{bl}(T_{sk} - T_{cr}) - Q_{res} \tag{1}$$

$$C_{sk}\left(\frac{dT_{sk}}{dt}\right) = C'(T_a - T_{sk}) + K(T_{cr} - T_{sk}) + \dot{m}_{bl}\, c_{bl}(T_{cr} - T_{sk}) \tag{2}$$

where M is the metabolic rate (concentrated in the core compartment), K is the core-to-skin conductance, C' is the skin-to-ambient conductance, W is the external mechanical power, Q_{res} is the heat loss from respiration, $\dot{m}_{bl}$ is the skin blood mass flow rate, c_{bl} the blood specific heat, T_a the ambient air temperature, C_{cr} and C_{sk} are the core and skin thermal capacitances, and t is time. While the core-to-skin conductance K is related to thermal conduction by direct contact between the core and skin, the skin-to-ambient conductance C' accounts for heat exchange between the skin and the environment through convection, radiation, and evaporation, and encompasses the effects of thermal and evaporative resistances of clothing [19].

Eqs. (1), (2) can be developed by introducing the relative mass of skin α (i.e., the fraction of body mass concentrated in skin compartment) and grouping some terms as follows

$$(1 - \alpha)\, m\, c_b\left(\frac{dT_{cr}}{dt}\right) = M_{net} + K'(T_{sk} - T_{cr}) \tag{3}$$

$$\alpha\, m\, c_b\left(\frac{dT_{sk}}{dt}\right) = C'(T_a - T_{sk}) + K'(T_{cr} - T_{sk}) \tag{4}$$

where m is the body mass, c_b the body specific heat, K' ($= K + \dot{m}_{bl}\, c_{bl}$) is the core-to-skin conductance inclusive of blood perfusion, and M_{net} ($= M - W - Q_{res}$) is the net metabolic rate, defined as the metabolic rate minus the mechanical power and minus the respiration heat losses. In such a way, the core and skin thermal capacitances C_{cr} and C_{sk} are linked to the total body thermal capacitance ($m\, c_b$) through the relative skin mass α, typically ranging from 0.1 to 0.3 [3].

As the skin temperature is regarded as the main indicator of the thermoregulatory response during running exercise, attention is focused solely on this key parameter.

2.1. First part of the thermal transient

Immediately after the onset of exercise (small t limit or early time period), cutaneous vasoconstriction and the subsequent redirection of blood flow to active muscles lead to a decrease in $\dot{m}_{bl}$ (and K'). This implies that the changes in skin temperature over time, governed by Eq. (4), are primarily influenced by the temperature difference between the skin and the surroundings:

$$\alpha\, m\, c_b\left(\frac{dT_{sk}}{dt}\right) \approx C'(T_a - T_{sk}) \tag{5}$$

After short passages, the first asymptotic solution for the skin temperature in the early period results to be

$$\frac{(T_{sk} - T_a)}{(T_{sk,0} - T_a)} = e^{-\frac{C'}{\alpha\, m\, c_b} t} \tag{6}$$

where $T_{sk,0}$ is the skin temperature at the start of exercise.

Eq. (6) shows that the skin temperature T_{sk} exponentially decreases toward the ambient air temperature T_a (presumed to be lower than the initial skin temperature) due to a skin vasoconstrictor response to exercise, without heat coming from the core compartment.

2.2. Second part of the thermal transient

As the exercise progresses, the undissipated heat stored in the core compartment causes an increase in core temperature T_{cr}. To ensure the core temperature remains within a safe threshold, beyond which organ and central nervous system functions may be impaired, the thermoregulatory system activates a vasodilator response to exercise which carries excess heat out of the body through the skin. During vasodilation, which characterizes the second part of the transient (large t limit or late time period), the rate of heat storage decreases, and the core temperature is likely to reach a quasi-steady platform. From Eq. (3), with $\frac{dT_{cr}}{dt} \approx 0$

$$M_{net} = K'(T_{cr} - T_{sk}) \tag{7}$$

and, from Eq. (4),

$$\alpha\, m\, c_b \left(\frac{dT_{sk}}{dt}\right) = C^{'}(T_a - T_{sk}) + M_{net} \tag{8}$$

The following solution for T_{sk} is readily achieved

$$\frac{(T_{sk} - T_a)}{M_{net}/C^{'}} = 1 - e^{-\frac{C^{'}}{\alpha\, m\, c_b} t} \tag{9}$$

Eq. (9) assumes, for $t \to 0$, $T_{sk} = T_a$ (as occurs in the limiting case of no heat flow from the core to the skin) and applies to time instants sufficiently far from the start of exercise. As $t \to \infty$, it follows that

$$T_{sk} = \left(T_a + \frac{M_{net}}{C^{'}}\right) \tag{10}$$

According to Eq. (10), the relative maximum of the second asymptotic solution for the skin temperature is controlled by the net metabolic rate and the conductance between skin and external environment.

Finally, the upper limit of core temperature, $T_{cr,max}$, can be obtained from the combination of Eqs. (7) and (10):

$$T_{cr,max} = T_a + M_{net}\left(\frac{1}{K^{'}} + \frac{1}{C^{'}}\right) \tag{11}$$

2.3. The intersection of the two asymptotes

Fig. 3 schematically shows the typical trends of core and skin temperatures, from their respective initial values ($T_{cr,0}$ and $T_{sk,0}$), throughout the exercise. The figure also illustrates the two asymptotic solutions for the skin temperature T_{sk}: in the early-time limit (*I*), skin temperature decreases due to vasoconstriction, while in the late-time limit (*II*), vasodilation leads to a subsequent increase in skin temperature.

The two asymptotes *I* and *II* sharply intersect at time t^*, which denotes the time instant (or, more precisely, its order of magnitude) corresponding to the attainment of minimum skin temperature, marking the transition from skin vasoconstriction to vasodilation. The exercise time t^*, at which cutaneous vasodilation begins, can be determined by combining Eq. (6) for transient *I* and Eq. (9) for transient *II*

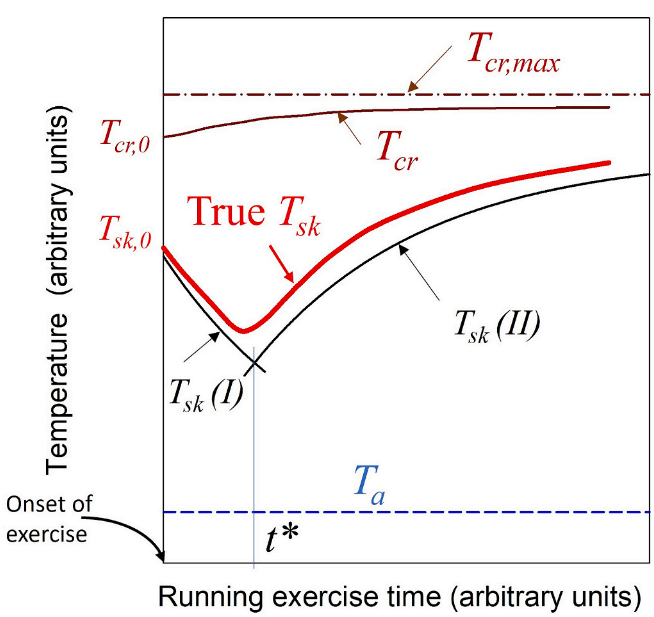

Fig. 3. Typical changes in skin and core temperatures over time during running exercise. The asymptotic curves (*I* and *II*) for skin temperature, the exercise time to cutaneous vasodilation t^*, the maximum core temperature $T_{cr,max}$, and the ambient air temperature T_a are also indicated.

$$T_a + (T_{sk,0} - T_a)\, e^{-\frac{C^{'}}{\alpha\, m\, c_b} t^*} = T_a + \left(\frac{M_{net}}{C^{'}}\right)\left[1 - e^{-\frac{C^{'}}{\alpha\, m\, c_b} t^*}\right] \tag{12}$$

to give

$$t^* = \left(\frac{\alpha\, m\, c_b}{C^{'}}\right) ln\left[1 + \frac{C^{'}(T_{sk,0} - T_a)}{M_{net}}\right] \tag{13}$$

Essentially, t^* increases with the ratio of the skin thermal capacitance $C_{sk} = \alpha\; m\; c_b$ to skin-to-ambient conductance $C^{'}$ and with the ratio of initial heat dissipation potential $C^{'}\,(T_{sk,0} - T_a)$ to net metabolic rate M_{net}.

Eqs. (6), (9), (10), and (13) provide a concise description of skin temperature changes over time throughout running exercise, accounting for physiological and environmental factors. In particular, the above equations are indicative of the asymptotic solutions for T_{sk} (and their point of collision), while the actual time-history of skin temperature ("true" T_{sk} in Fig. 3) can be derived from the solution of Eqs. (1) and (2) without restrictive assumptions. To enhance understanding of the model based on asymptotic solutions, the flow chart in Fig. 4 has been included.

3. Results and discussion

The two competing asymptotes reflect two different thermal responses of the skin during the running exercise. The application of the method of intersecting the asymptotes [4] identifies the most convenient time instant for the human body to switch the blood peripheral vasoconstriction to vasodilation in response to the exercise and, more important, permits to infer the possible time-evolution of skin temperature during exercise based on the two extreme asymptotic trends, reflecting the influence of key physiological and environmental factors. The ability of the asymptotic curves to predict, through the sharp intersection of their vastly dissimilar trends, the exercise time to cutaneous vasodilation t^* and to capture the characteristics of the experimental skin temperature changes with time, was demonstrated by Tanda [19]. As shown in ref. [19], the two asymptotic limits reasonably represent measured T_{sk} for a subject running on treadmill at two different velocities (and therefore different net metabolic rates) but under the same environmental conditions. Additionally, for two subjects running on treadmill at the same velocity and environmental conditions but with different levels of training, both the calculated asymptotes and the measured data for T_{sk} showed that the less trained subject experienced a prompt vasodilator response (likely associated with a higher metabolic rate), unlike the more trained subject.

The primary objective of this study was to highlight the role exerted by main physiological and environmental factors on dynamic thermoregulation during running exercise. Fig. 5 (left-hand side) synthetically shows how crucial parameters affect the trends of the two asymptotic solutions. The initial temperature decay (transient *I*) is regulated by skin-to-ambient conductance, initial skin-to-ambient temperature difference, and skin thermal capacitance. Increasing the first two factors, primarily influenced by environmental conditions, accelerates skin temperature decrease. Conversely, an increase in skin thermal capacitance, associated with the subject's mass, mitigates the decline in skin temperature. In contrast, the slope of skin temperature rise during transient *II* is chiefly governed by the net metabolic rate, a physiological factor not involved in transient *I*, in conjunction with skin thermal capacitance. An increase in the former or a decrease in the latter triggers a prompt switch to vasodilation and an increasing slope of the skin temperature rise associated with vasoregulation purposes. Finally, the asymptotic threshold toward which skin temperature tends as the running exercise progresses depends on ambient temperature and the ratio between net metabolic rate and skin-to-ambient conductance. A higher net metabolic rate during exercise prompts a thermoregulatory response leading to increased skin temperature; however, this effect is

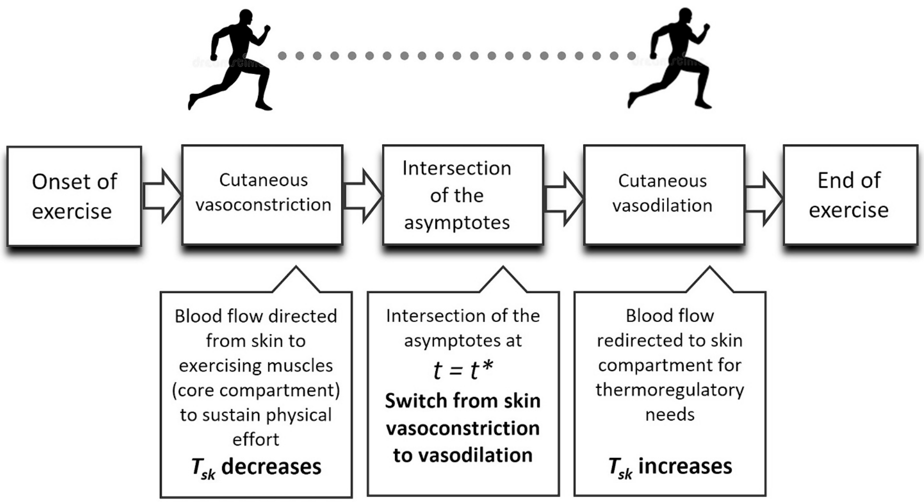

Fig. 4. Flow chart illustrating the model for skin temperature changes during running exercise using the intersection of asymptotes method.

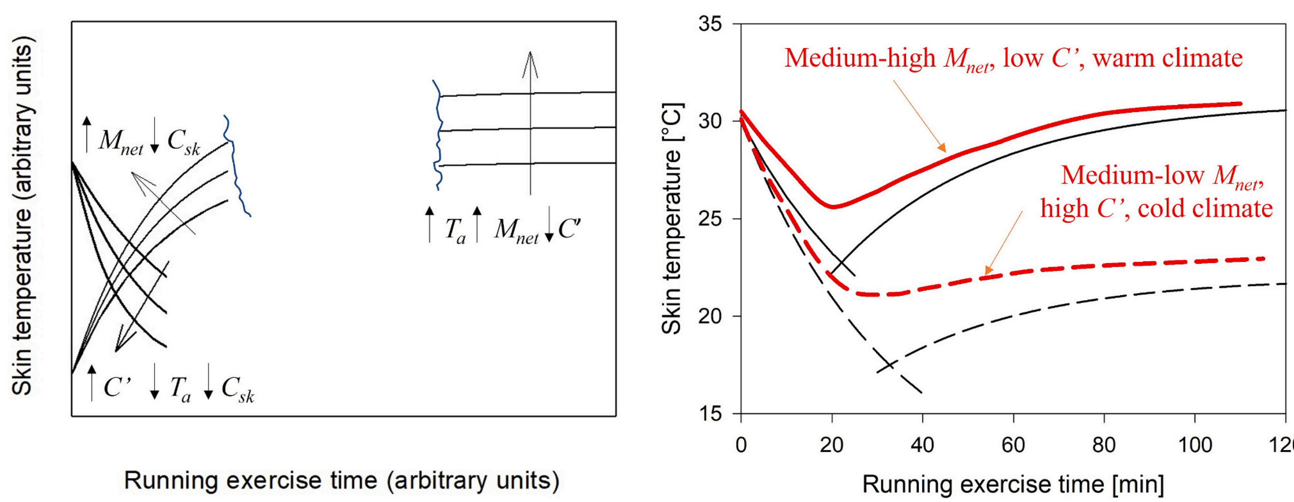

Fig. 5. Effects of main physiological and environmental factors on the asymptotic curves (left) and on real skin temperature changes during exercise (right).

tempered in cooler environments and by a relatively high skin-to-ambient conductance.

Two representative skin temperature profiles are depicted on the right-hand side of Fig. 5, along with their respective asymptotic limits. According to the model described herein, a subject running at a relatively high speed (with high metabolic rate production), and/or in calm and relatively hot (and humid) air, will experience a markedly different evolution of skin temperature over time compared to a running exercise sustained, even by the same subject, at a lower effort (lower running speed and associated metabolic heat production), and/or in a relatively cold environment. In the former case, skin temperature, after the initial decrease, is compelled to rise to meet thermoregulatory needs (such as dissipating accumulated heat) while, in the latter case, skin temperature remains stable or increase only slightly. These two scenarios, frequently encountered in documented experimental circumstances, do not necessarily reflect measurement errors or indicate the effects of heterogeneous methodologies and non-standardized environmental conditions. Instead, they may be attributed to the combined influence of various physiological and environmental parameters involved in the phenomenon. These parameters, acting together, yield a skin temperature at the end of exercise that can be lower, equal, or even higher than the pre-exercise one. Therefore, simply observing skin temperature at the beginning and end of exercise (without analyzing its time-history throughout the exercise) is likely to overlook the influence of exercise on skin temperature.

4. Future developments and concluding remarks

A method based on the intersection of asymptotes has been proposed to understand skin temperature changes with time during running exercise. The primary objective of this study was to comprehensively establish a scientific rationale for the varied skin temperature fluctuations reported in the literature during running exercises under different intensities and environmental conditions, which often contradict one another. Furthermore, the study aims to outline the role of the key variables influencing skin temperature in a straightforward manner.

Two asymptotic expressions for skin temperature during the initial and the last phases of the exercise have been derived from the energy balance in dynamic conditions. The first transient solution is influenced by cutaneous vasoconstriction associated with exercise, while the second is driven by the subsequent stimulus to vasodilation linked to thermoregulatory response. Consequently, the two asymptotes exhibit significant dissimilar trends, with their sharp intersection indicating the transition from skin vasoconstriction to vasodilation. The approximate fit of the skin temperature evolution over time to its two clashing asymptotes suggests that environmental factors primarily influence the early stages of exercise, characterized by a decrease in skin temperature, while physiological factors (such as metabolic rate and skin thermal capacitance) become more significant as the exercise progresses. The combination of these influential parameters helps interpret the skin temperature changes observed during exercise, often markedly different from each other, as reported in experimental studies in the literature.

A potential implementation of the proposed method could involve incorporating the dew-point temperature of the environmental air, as the primary mechanism for heat dissipation from the skin to the environment during running is through evaporative losses, which are only partly influenced by the skin-to-ambient air temperature and are more accurately associated with the skin-to-dew-point temperature difference. Additionally, accounting for solar radiation, a significant incoming heat source, can greatly impact the thermoregulatory response during outdoor running, especially if its intensity is notable. While these adjustments to the model may compromise its simplicity to some extent, they can lead to a more precise evaluation of the competing asymptotic trends in skin temperature during running exercise.

As a future direction for this line of research, the methodology could potentially be adapted to study thermoregulatory responses during other aerobic activities, such as biking or rowing. Moreover, it could be applied to other biological systems involving mammals, such as exercising dogs and horses, whose energy balance is governed by similar time-dependent relationships.

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CRediT authorship contribution statement

Giovanni Tanda: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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