

Chapter 5

The Use of Infrared Thermography in the Study of Sport and Exercise Physiology

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Abstract Infrared thermography (IRT) is considered an upcoming, promising methodology in the field of exercise physiology. Skin temperature distribution derives from muscular activity, skin blood flow as well as perspiration patterns in specific body parts. This chapter aims to provide a general overview on the literature about the study of the skin temperature response to exercise assessed by means of IRT and its relationship with other thermoregulatory variables, exercise characteristics and performance factors.

5.1 Introduction: Why Is Important to Monitor Skin Temperature in Sport and Exercise Physiology?

At rest, human presents a thermal homeostasis by the regulation of core temperature in values about 36.8 °C [1]. This regulation is managed mainly by the hypothalamus, which receives sensory inputs from central and peripheral sites, and it activates or inhibits the parallel efferent thermoregulatory pathways [2]. However,

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physical exercise and repetitive effort is a challenge to thermal homeostasis [1, 3, 4]. It is well established that physical activity induces complex thermoregulatory processes where part of heat in excess is dissipated through the skin to the external environment [3]. During exercise, the thermoregulatory control of skin blood flow has the fundamental role to maintain normal core temperature and leads to changes in hemodynamics affecting thermal signals [5, 6]. Skin temperature is the result of the heat transferred by the skin blood flow, thermoregulatory responses of heat dissipation such as conduction, convection, radiation and sweat evaporation, environmental conditions, and different biophysical factor such as body surface area or body composition [7, 8]. Therefore, measuring skin temperature provides useful information about the complex thermal control systems.

Research attention has been devoted especially to understand mechanisms limiting performance during exercise in hot and warm environment [4, 9–11]. Among the mechanisms limiting performance during exercise at submaximal intensities in the heat, cardiovascular factors play an important role [3, 9]. Researches have put emphasis on the limitations related to the Central Nervous System (CSN), and the role of high core temperature [9, 12–14]. It has been proposed that high core temperature (~ 40 °C) would be the primary factor affecting CNS, thus limiting aerobic performance at submaximal intensity [9, 10, 12, 14].

While the increase in core temperature occurs proportionately to the exercise intensity, skin temperature is mainly related to environmental conditions and the heat loss capacity [11, 15, 16]. An increase in core temperature during exercise affects also skin temperature, as heat in excess is transferred from the inner to the superficial parts of the body via cutaneous vasodilation, where is dissipated thorough the skin [17]. Therefore, an isolated increment in skin blood flow accompanies an increment in skin temperature [18]. However, this increment in skin blood flow is commonly accompanied by other processes, such as sweat evaporation. As in many situations, skin temperature can result in a decrease instead of an increase.

However, studies supporting the hypothesis of the critical core temperature were conducted inducing simultaneously high core and skin temperatures [9, 10, 12]. During a lot of time, it was assumed that core temperature was the main responsible of fatigue during aerobic exercise in the heat. However, in the last years this theory has been questioned showing that skin temperature has also an important role, and therefore, the emphasis in research was shifted towards the role of skin temperature [11]. It has been recently demonstrated that the relationship between skin temperature and core temperature, and not only core temperature, has a key role in limiting exercise performance [11, 19]. In particular, critical reduction in the core to skin temperature gradient is the “primary” factor responsible for impaired aerobic capacity, rather than a critical core temperature. [11, 19].

Based on these evidences, in the last years research attention has been devoted on studying the thermal balance between the human body and the environment during exercise through the assessment of skin temperature. During the initial phases of the exercise, skin temperature tends to decrease due to the cutaneous vasoconstrictor response to exercise [20]. After that, skin temperature primarily

increases when blood flow shifts from internal tissues to the skin, thus dissipating heat in excess related to an increased metabolic activity [21, 22]. Nevertheless, especially in moderate environments, skin temperature may decrease due to heat dissipation by convection, radiation and evaporation [23, 24].

All in all, skin temperature in specific regions of the body is the result of a thermal balance between muscle activity, vasodilation and sweat evaporation [3, 24].

This chapter aims to provide a general overview on the literature about the study of the skin temperature response to exercise assessed by means of infrared thermography (IRT). More specifically, the chapter is made in order to provide the reader with an understanding of the effect of exercise on skin temperature. Specifically, some important factors that affect the behaviour of skin temperature during exercise and sport will be presented and discussed, as well as some of the most significant studies on infrared thermography to date. In order to fulfill all the above points, the chapter is structured as follows:

1. First, the chapter will discuss some methodological issues that could affect the skin temperature behaviour during exercise, such as the instrument used (e.g., thermal contact sensors or IRT) as well as the characteristics of the exercise.
2. Second, the chapter will show the relationship between the skin temperature and other thermoregulatory variables (i.e., blood flow, core temperature and sweat rate).
3. Third, the chapter will review the effect of the exercise on skin temperature in relation with different experimental and exercise conditions.
4. Finally, the chapter will show the relationship between skin temperature and performance variables (VO_{2max} , heart rate, neuromuscular activation and body composition).

5.2 Measuring Skin Temperature in Exercise Physiology: Methodological Aspects

5.2.1 Measurement Instrument: Contact Thermal Sensors Versus Infrared Thermography

Typically, skin temperature is measured using contact thermal sensors, such as thermocouples or wired thermistors, usually considered as gold standard methods (despite its limitations, as this section will show). A thermocouple is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more joint locations. Their system is based on the Seebeck effect, which occurs when a difference in electric potential is created between two conductor materials at different temperatures [25, 26]. Thermistors are resistors in which resistance varies with temperature, allowing stored calibration data within the

circuit to convert this to a temperature value. Thermistors and thermocouples are non-invasive, but the associated wiring requires familiarisation and a hard-wired connection to a computer, thus making difficult skin temperature monitoring during dynamic conditions, such as during dynamic movements [27].

In recent years, thermocouples have been also developed in wireless system, providing a solution to the limitations of hard-wired methods. In fact, wireless sensors provide subjects with great mobility as they do not interfere with their movements, such in case of physical exercise during high dynamic situations, both in laboratory and in the field [26, 28]. These sensors allow also measuring below or in-between clothing layers [29].

Although contact thermal sensors presents some advantages, there are some limitations in its use. Determining temperature in just one single point can limit the understanding of human thermal response, as the evaluated body part could be not properly represented [30]. Furthermore, thermal interactions between contact sensors and environment can affect the reliability of the measurements [26]. Contact sensors are usually attached to skin using different types of clinical tapes. The attaching method of contact sensors to the skin has been shown to affect the local heat transfer [31, 32], thus influencing the local thermal regulation and skin temperature [28, 33].

An alternative device to measure skin temperature is IRT. IRT has become popular in the last years in sport and exercise physiology research due to its non-contact and non-invasive character. Furthermore, IRT obtains a thermal image, which can measure the temperature at all points, thus allowing to measure large areas instead of single points (such as contact sensors) [28, 30]. As can be seen, IRT can solve some of the limitations of contact sensors. For this reason, apart from studies applying IRT in the measure of skin temperature modifications related to exercise, in the recent years research attention has been devoted also to investigate the validity of IRT against thermal contact sensors during both resting and exercising condition [27, 28, 30].

De Andrade Fernandes et al. [28] published a study aimed to compare the mean skin temperature measured using thermocouples to those measured using IRT and to check the agreement between the two methods before, during and after exercise performed in thermo-neutral environment. Two identical experimental protocols were performed in two different days, one with the thermocouple measures, and one with the IRT measures. In each of the two days, the subjects completed an interval test on a treadmill consisting of 12 blocks of 5 min, each one separated by an interval of 1 min, during which temperature was measured. The exercise intensity was individually fixed to 60% of the VO_{2max} speed obtained in the pre-session experiment.

Low agreement between the mean skin temperature values measured using thermocouples and IRT was found in each of the three phases considered (before, during and after exercise), demonstrating the discrepancies between the two methods. Thermocouples showed higher mean skin temperature values during exercise than IRT, while IRT showed higher values before and after exercise. The results indicated that the interpretation will vary depending on the method employed (Fig. 5.1). The authors suggested that the low agreement between

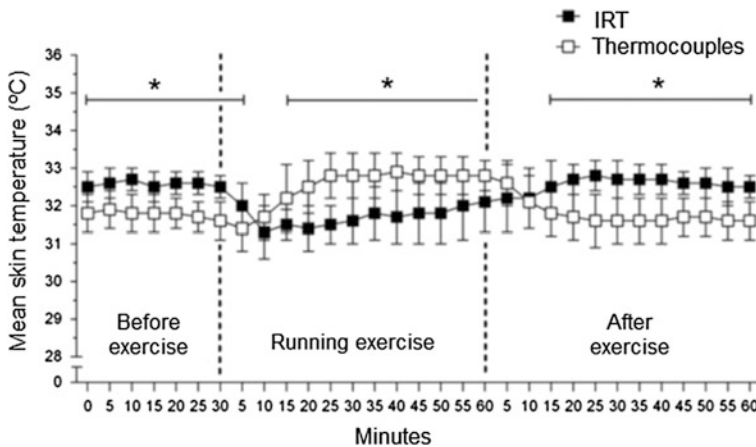


Fig. 5.1 Mean skin temperature values pre-, during and post-exercise obtained from thermocouples and IRT. Significant differences between methods are shown using *. Figure modified from de Andrade Fernandes et al. [28]

thermocouples and IRT could be mainly due to the contact character of thermocouples. In fact, several factors could contribute to explain the observed differences: the pressure exerted by fixation methods and the use of substances for the fixation [33]. Furthermore, increased heat loss by convection and evaporation in those regions where thermocouples were fixed could contribute to increase the mean skin temperature measured by thermocouples [31, 33].

Another study investigated the agreement between hard-wired thermistors, telemetry thermistors (i.e., wireless sensors), and IRT during exercise in a hot and humid environment [27]. Subjects performed an incremental running exercise test in a climatic chamber with an environmental temperature of 31.9 ± 1 °C and relative humidity of $61 \pm 8.9\%$. Skin temperature was measured at four different sites (i.e., chest, arm, thigh, calf), and mean skin temperature was computed with the weighted average: chest 30%, arm 30%, thigh 20%, and calf 20% [34]. Exercise started with speed between 8 and 10 km h⁻¹. Each subject completed five stages of three minutes, with speed increasing by 1 km h⁻¹. At the end of each stage, subjects straddled the treadmill and the thermal camera recorded skin temperature at each site. The authors concluded that IRT tended to under-estimate the temperature values measured by hard-wired thermistors. Authors suggested that the differences between methods could be due by the contact and fixation of the thermistors as in the previous study, but mainly by a measurement error of IRT due to the alteration of the skin emissivity by the sweat. Due to this interpretation, the authors suggested that IRT may be a useful tool for measuring skin temperature in static and controlled environments, but its use is not recommended for live monitoring during dynamic conditions, such as during exercise.

More recently, another study compared IRT and thermal contact sensors for measuring skin temperature in various parts of the body in a moderate cycling

scenario and subsequent cooling down phase [30]. Furthermore, the novelty of this study is that the authors compared the results of human scenario with a more controlled scenario: surface temperature of a hot plate system during dry and wet conditions. This instrumented test was conducted to exclude human thermoregulatory processes when simulating heat exchange in dry and wet conditions. The exercise test protocol was structured in the following phases and is resumed in Fig. 5.2:

1. Thermal adaptation phase (15 min): Standing in the laboratory. The investigator attached the skin temperature sensors within the first minutes of this phase. Thermal images were recorded at the end of this phase (Pre-cycling).
2. Cycling phase (48 min): After warming-up for 3 min at 50 W and 90 rpm, participants cycled at 50% of their maximal power output at 90 ± 3 rpm. Thermal images were recorded immediately at the end of the exercise (Post-cycling).
3. Cooling-down phase (10 min): Standing in the laboratory. Thermal images were recorded at the end of this phase (Post-cooling).

Immediately after cycling, IRT provided lower temperature values with respect to thermal contact sensors, whereas it presented higher temperatures after the cooling-down phase [30]. In the exercise trial, the correlation coefficient between the two methods was high when measured before cycling ($r = 0.92$) whereas it was reduced immediately after cycling ($r = 0.82$) and after the cooling-down phase ($r = 0.59$). However, the discrepancies in temperature between the two methods remained within the accuracy of the thermal camera (± 2 °C). Comparable results were observed between dry and wet states when comparing exercise test and instrumented tests, in which no water coating was present, suggesting that in such exercising scenario, sweat delivery was not high enough to produce a continuous water layer on the skin. Furthermore, they suggested that the comparable differences between the instrumented test and the human scenario are showing that differences between both methods are mainly related to the effect of the contact sensors on the reduction of heat loss (via radiation and sweat evaporation). The authors stressed that these findings demonstrate the possibility of using IRT in the field of sports and exercise physiology for assessing skin temperature.

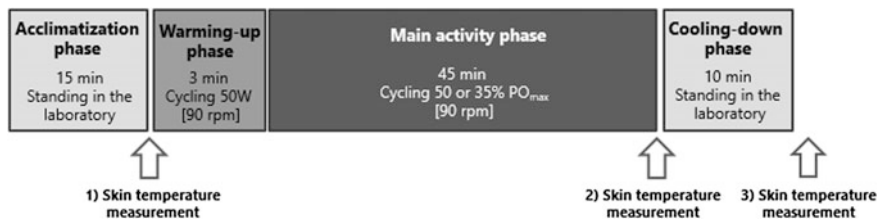


Fig. 5.2 Experimental protocol of the study (PO_{max} corresponds to the peak power output if pedaling at 90 rpm determined in pre-test). Figure adapted from Priego Quesada et al. [30]

Based on the findings of these methods-comparison studies, IRT seems to be appropriate for measuring skin temperature modifications associated to exercise. IRT allows to measure skin temperature distribution with high sensitivity (0.05 °C), thus having the main advantage to be capable of analysing large and thus, more representative areas on the body surface. Due to its non-invasiveness, heat transfer process at skin level is not affected by attachment of sensors. Nevertheless, thermal contact sensors have some advantages with respect to IRT, especially when measuring absolute temperatures in particular setting conditions. For example, contact sensors have the possibility to measure temperature when subjects are clothed, or when body posture and space do not allow having optimal conditions to record infrared thermal images [30]. Furthermore, sweat on the skin produced during and after exercise may act as a filter for infrared radiation and that could lead to an error in the estimation of the skin temperature using IRT [35]. However, this issue needs future studies to explore the real physical effect of the sweat on the calculation of skin temperature using IRT in the different exercise scenarios.

To conclude this section, it is important to take into account that advantages and disadvantages of both methods should be considered before designing a study assessing skin temperature changes associated to exercise, and cautions should be taken to control possible sources of error. Furthermore, it is important to consider the measurement method during the interpretation of the result of one study.

5.2.2 Exercise Characteristics and Experimental Approach

In the last decades, many authors have described the skin temperature response to exercise in different body areas under different conditions and different experimental approaches [16, 36–42]. Although drawing a certain conclusion on the skin temperature response to exercise seems to be difficult due to huge discrepancies between studies in aim and methodology, it is generally accepted that skin temperature modification associated to exercise—and its physiological meaning—varies in relation to several factors. Among them, the most relevant are characteristics of the exercise and different experimental approaches.

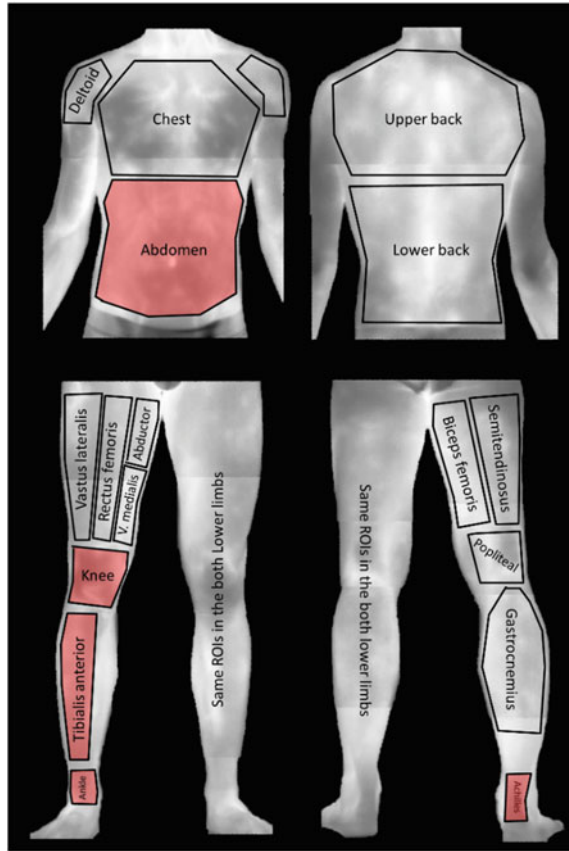
In general, exercise can be classified on the basis of the discipline (i.e., the type of discipline studied, such as running, cycling, or specific resistance exercise). For example, Merla et al. [40] investigated the skin temperature response to running exercise, as well as Priego Quesada et al. [41] did for cycling exercise. However, in the case of resistance exercise, it is important to distinguish between singlejoint resistance exercise and multijoint resistance exercise. Singlejoint exercises usually isolate a specific muscle or muscle group (such as leg extension), whereas multijoint exercises usually recruit one or more large muscle groups as agonist muscles (such as squat), and other muscles as coacting muscles (for example for stabilization). Most sport activity and daily movements consist of multijoint movements. The more similar the training activity to the actual sport and daily movements, the greater positive transfer of resistance exercise to these movements (i.e., the

specificity concept). In general, from both scientists and practitioners point of views, multijoint exercises are considered more suitable for improving sport and daily performance with respect to single-joint exercises [43]. The fact of recruiting single muscle group (singlejoint exercise) rather than large muscle groups (multijoint exercise) is likely to differently influence thermoregulatory processes (especially vasoregulation), thus in turn to influence also skin temperature response to exercise in different way. As regards to the study of the skin temperature response to singlejoint and multijoint exercises, both are present in the literature. For example Formenti et al. [39] studied the skin temperature response of anterior thigh to a typical multijoint exercise, such as squat; on the other hand, Ferreira et al. [37] investigated the skin temperature response on posterior thigh to a single joint exercise (knee flexion).

Furthermore, it has been shown that skin temperature response varies according to the intensity and the duration of the exercise. For example, Balci et al. [36] examined the difference in the skin temperature dynamics during a submaximal constant load cycling exercise and a maximal incremental cycling exercise. It was found that the skin temperature time course during the two trials exhibited a different dynamic. On the other hand, Priego Quesada et al. [16] assessed the effect of different cycling workloads on core and skin temperature. They observed that cycling workload did not have any effect on the skin temperature in the almost totality of the body regions due to the higher heat loss of the thermoregulatory system, and only Regions of Interest (ROIs) that are mostly constituted by connective, bone and fat tissues were affected (Fig. 5.3). These ROIs presented higher reductions of the skin temperature at the higher workload (50%). The authors suggested that these regions, that are not located on top of active muscles, are affected by a temperature decrease due to a higher overall sweat rate according to a higher intensity, rather than temperature increases through rising workloads. On the other hand, core temperature increased continuously throughout the exercise, as expected.

Investigations have been conducted with the aim to study localized effect of the exercise, or systemic effect of the exercise. These are different experimental approaches, which are both present in the literature. For instance, Zontak et al. [42] measured the skin temperature response of hands before, during and after two bouts of cycling exercise. In this study, while the cycling exercise involved only lower limbs, the skin temperature was measured on the hands. Thanks to this approach, the authors were interested in studying the systemic effect, since the skin temperature was measured over parts of the body not involved in the exercise directly. Another experimental approach was used by Formenti et al. [38], which compared the skin temperature response to standing calf rise exercise in a sample of trained and untrained subjects. In this paper, the authors aimed to study the localized effect of the exercise, since skin temperature was measured on the calves area of the subjects, i.e., the muscle tendon unit directly involved in the exercise movement. A simultaneous evaluation of systemic and localized effect is also possible since both measurements can be combined in the same study. For example, Priego Quesada et al. [16] investigated the influence of cycling workload on core and skin

Fig. 5.3 ROI representation of the differences in the variation of skin temperature between 50 and 35% PO_{max} , using a red background in the ROI, in the study of Priego Quesada et al. [16]



temperature measured in seventeen different regions of interests on lower limbs (i.e., over the muscles involved in exercise) and on the trunk.

Moreover, the experimental approach is different when researchers are interested in studying the dynamic of the skin temperature time course during exercise, or when researchers are interested in a pre-post exercise comparison of skin temperature. These are different methodological approaches to the problem, with different physiological meanings. Merla et al. [40] measured skin temperature of various parts of the body continuously during running exercise using a sampling rate of 50 Hz. The authors were clearly interested in studying the dynamic of skin temperature changes occurring throughout the duration of the exercise. Conversely, a pre-post comparison approach was used by Priego Quesada et al. [41], which investigated the relationship between neuromuscular activation (measured using surface electromyography) and skin temperature (measured using infrared thermography) during cycling exercise. In this study, three thermographic measurements were performed in different moments of the experiment: before the cycling test, immediately after the cessation of the cycling test, and 10 min after the

cessation of the cycling test. This approach is usually followed by a type of analysis considering the skin temperature variation, as follows [16, 41]:

- ΔT : Difference between temperature immediately after the cycling test and before, expressed in °C.
- ΔT_{10} : Difference between temperature 10 min after the cycling test and before, expressed in °C.
- ΔT_{after} : Difference between temperature 10 min after the cycling test and immediately after, expressed in °C.

All in all, among the variables influencing skin temperature modifications associated to exercise, exercise characteristics and experimental approach are probably the most relevant, and those that researchers should be aware when designing experiments.

5.3 Relationship of Other Thermoregulatory Variables with Skin Temperature During Exercise

Skin layer constitutes the interface between the human body and the external environment. It plays a fundamental role in thermoregulation processes, thus regulating heat transfer produced by metabolism between the core to the external thermal conditions of environment [44]. Modifications of skin temperature are primarily modulated by skin perfusion, which is a function of microvascular anatomy and vasoactive control of the autonomic nervous system [2, 5]. Under conditions of hyper thermic stress, skin blood flow can be regulated, thus increasing in the skin surface for transfers of heat from the body, and the sweat rate increases to dissipate the heat from the skin to the environment [2]. Conversely, under cold environments, cutaneous vasoconstriction is produced and the skin plays the role of insulating the body from external environment [2].

Infrared imaging provides a visual map of the skin temperature of the body surface. However, it is worth noticing that an infrared image cannot quantify measurements of skin blood flow. The infrared image provides a map of temperatures of the skin, which in turn is a function of blood perfusion to the surface area [45]. Nevertheless, thermal changes on the skin may also be influenced by external thermal stressors. Therefore, skin temperature is the result of a complex interaction between skin blood perfusion, environmental temperature, heat loss processes and biophysical characteristics [7, 8].

The process of repeated and/or sustained contraction of the muscles during an exercise bout produces heat, leading to an increase in body temperature [21, 46]. Therefore, during exercise thermoregulatory reflexes are activated with the aim to reduce body temperature, and to maintain thermal homeostasis [2]. Cardiovascular system during periods of exercise aims to provide sufficient amounts of oxygen and nutrients to the active muscle [3]. To this purpose, as exercise begins, muscles

involved in exercise rapidly require increased oxygen delivery. This need is mediated by the sympathetic stimulation of vessels in those areas where blood flow can be recruited (e.g., splanchnic and renal circulations), thus increasing blood flow in the exercising muscles. Meanwhile, thermoregulatory reflexes, aiming to reduce body temperature, lead to an increase in skin blood flow [2]. Therefore, thermoregulatory reflexes induced by the thermogenic effect of the exercise are in conflict with non-thermoregulatory cardiovascular responses to exercise [20]. For instance, during intense exercise and/or during exercise in warm environment, there is a competition between thermoregulatory and non-thermoregulatory reflexes. The first for increasing blood flow to the skin, the second for increasing blood flow to the active muscles. In general, these competing demands are resolved thanks to the increase in cardiac output [3]. However, increasing cardiac output may not be enough to resolve deficits resulting from combined intense exercise and heat stress (also when the dehydration is present), thus possibly leading to cardiovascular collapse [3].

The sympathetic control of skin blood flow is unique as there are sympathetic vasoconstrictor fibers (similar to those present in skeletal muscles) and sympathetic active vasodilator fibers in the skin surface. During exercise, as body core temperature rises, there is an initial vasoconstriction response caused by the increased demand of blood flow to the active muscles. However, once a specific body core temperature threshold is reached, skin blood flow begins to increase by the activation of the sympathetic active vasodilator response. Such increase in skin blood flow during exercise aims to promote heat loss, because blood flow is the first mechanism of heat transfer from the inner part of the body to the skin. Therefore, an increase in skin blood flow is likely to accompany an increase in skin temperature when sweat evaporation is not present.

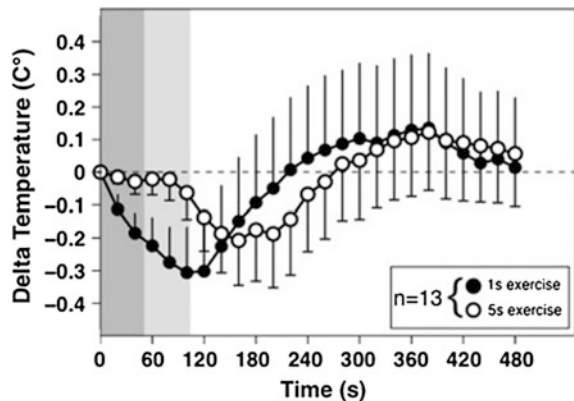
Acute thermoregulation adaptations to exercise have been extensively studied by monitoring skin blood flow [6, 47, 48]. However, exercise is associated with large hemodynamic responses involving a series of thermoregulatory processes. Since exercise causes heat production within the body and invokes cutaneous thermo-regulatory processes, modifications of skin temperature associated to exercise can be monitored by infrared thermography. Recent studies have investigated the interaction of skin temperature measured by thermography with other variables influencing thermoregulation in response to exercise. Three studies will be presented and discussed briefly [16, 39, 40].

Priego Quesada and colleagues [16] investigated the relationship between core and skin temperature measured in different sites of the body. Fourteen cyclists performed two 45-min cycling tests at 35 and 50% of peak power output on different days, with a constant cadence (i.e., 90 rpm). Core temperature was measured using an ingestible pill continuously throughout the test. Local skin temperature was recorded using infrared thermography before, immediately after, and 10 min after the end of the cycling tests. In general, from pre to post exercise skin temperature decreased in trunk regions, whereas increased in lower limb regions. Core and local skin temperatures showed moderate negative correlations for regions presenting the highest sweat rates over the body (such as trunk) whereas some

positive correlation were observed in regions in which sweat production was low (lower limbs). These findings highlight the difficulty of finding a relationship between skin temperature and core temperature, probably due to the thermoregulatory system efficiency in the increase of the thermal gradient (i.e., the difference between core and skin temperature) [11, 19], together with the multifactorial nature of the skin temperature [8, 30].

In another paper, Formenti and colleagues [39] studied the skin temperature response to two types of resistance exercises modulating the amount of skin blood flow. The rationale was that low intensity resistance training with slow movement and tonic force generation has been shown to create blood flow restriction within muscles (and therefore an important muscle de-oxygenation), thus maximizing the hypertrophic response even with low intensity. This condition of restricted muscle blood flow may affect skin blood flow, and in turn thermoregulation through the skin. Therefore, the authors investigated the effect of two speeds of exercise execution on skin temperature dynamics using infrared thermography. Thirteen active males performed randomly two sessions of squat exercise (normal speed, 1 s eccentric/1 s concentric phase, 1 s; slow speed, 5 s eccentric/5 s concentric phase, 5 s), using $\sim 50\%$ of 1 maximal repetition. Thermal images of skin temperature of the muscles quadriceps were recorded before the exercise (to determine basal skin temperature) and for 480 s following the initiation of the exercise (to determine the non steady-state time course of skin temperature). In summary, this study showed that squat exercises performed at two different speeds (1 s vs. 5 s) until exhaustion determined different profiles of skin temperature of the muscles quadriceps. Although the two exercises determined comparable maximal excursions of skin temperature, the rate of change of skin temperature was strongly reduced during the 5 s exercise as compared to the 1 s exercise (Fig. 5.4). Since the 5 s exercise mimicks a condition of blood flow restriction within the muscle, these data provided a detailed portrait of the skin temperature modifications associated with this condition, thus laying the basis for similar investigations using IRT coupled with Doppler flowmetry.

Fig. 5.4 Skin temperature variation from baseline recorded during 1 s exercise and 5 s exercise speed of a squat exercise. *Dark grey* and *light grey* bar represent the mean duration of 1 s exercise (55 s) and 5 s exercise (100 s), respectively. Figure obtained from Formenti et al. [39]



In the study by Merla et al. [40], the authors investigated the whole body anterior skin temperature modifications in well-trained subjects during an incremental running test until exhaustion. Fifteen males volunteers performed an incremental treadmill test until reaching their individual maximal heart rate. Skin temperature of total body was continuously monitored by infrared thermography. Skin temperature decreased as the subjects began the exercise, whereas a further skin temperature decrement occurred with the progress of the exercise. This was attributed to the continuous vasoconstrictor response, attributable to an increase in catecholamine and other vasoconstrictor hormones released as the exercise intensity increases [49, 50]. Thighs and forearms exhibited the earliest response. At the exercise interruption (i.e., at exhaustion), skin temperature values were 3–5 °C lower with respect to the baseline, and began to increase during recovery. Thighs and forearms exhibited the faster increase, followed by the total body skin temperature increase. Thermal images documented the presence of hyperthermal spots due to the presence of muscle perforator vessels during recovery (Fig. 5.5). The diffusion of heat from the hyperthermal spots to the surrounding cutaneous tissue suggests a possible hemodynamic and thermoregulatory role for the perforator vessels during/after exercise [51]. The findings of this study indicate that infrared thermography permits the quantitative evaluation of acute cutaneous whole body thermal adaptations occurring in response to an incremental exercise until exhaustion. It is such an incremental character of the exercise that caused a continuous vasoconstriction response, thus requiring blood flow to the active muscles from the other parts of the

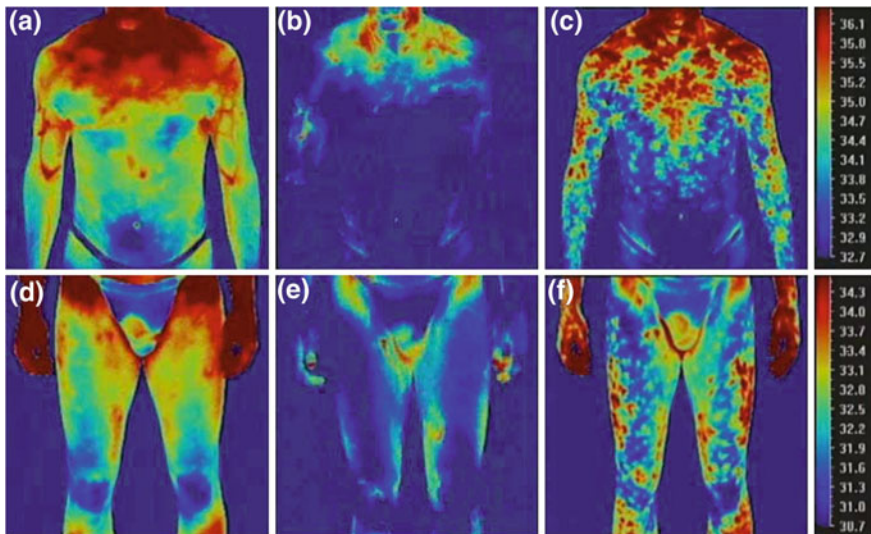


Fig. 5.5 Anterior view of the upper and lower body of a representative participant taken before running (a, d), immediately after reaching the age-predicted maximal heart rate value during incremental running test (b, e); and during recovery from exercise (c, f). Figure obtained from Merla et al. [40]

body. However, the continuous decrease in skin temperature observed during exercise should be attributed not only to the decrease in skin blood flow, but may be also related to a small amount of sweat delivery, even it seems to play a secondary role [30].

All in all, the interpretation of the dynamic process of skin thermal regulation obtained from thermal imaging requires a basic understanding of physiological mechanisms of skin blood flow and factors that influence thermoregulation processes. Researchers have combined the use of infrared thermography with techniques providing more direct measurements of blood flow, to better understand the complexity of thermoregulation processes. For this purpose, a study by Merla et al. [52] proposed a non-invasive method to calculate blood flow by means of thermal infrared imaging and bio-heat transfer modeling. The method, able to provide high time-resolution series of cutaneous blood flow images, was tested against a standard laser Doppler imaging system, which is considered the gold standard for non-invasive assessment of skin blood flow, on both healthy subjects and patients suffering from systemic sclerosis [52]. However, to the best of our knowledge, no studies have combined the measure of skin temperature by infrared thermography with the measure of skin blood flow by laser Doppler during exercise. This should be the further step for advancing the knowledge about the thermoregulatory processes occurring at the skin level during different types of exercise and/or conditions.

5.4 Effect of the Exercise Characteristics on Skin Temperature Response

As it was mentioned in the previous sections of this chapter, skin temperature could present increases or decreases depending on the characteristics of the study and the ROI investigated. In order to understand all the factors that could affect the skin temperature behaviour during exercise, first it is important to check the heat balance equation, i.e., an equation that it is often used in the in mathematical calculation of thermoregulation:

Heat production = Heat loss, and more specifically :

$$M - W = (K + C + R + ESK) + S$$

where M is the rate of metabolic heat production, W is the rate of mechanical work, K is the rate of conductive heat loss, C is the rate of convective heat loss from the skin, R is the rate of radiative heat loss from the skin, ESK is the rate of evaporative heat loss from the skin, and S is the rate of body heat storage.

Higher values on one side of the equation could explain greater increases or reductions in skin temperature. Thus, high increases of skin temperature would be explained by high heat production and low capacity of heat loss, and high

reductions by low heat production and high capacity of heat loss. Below there is a summary of what are the factors that affect heat production and heat loss:

- Heat production (metabolic rate—mechanical work): metabolic cost of the exercise, duration and intensity.
- Heat loss: heat dissipation by conduction, convection, radiation, and evaporation, and external work. At the same time, these processes depend mainly on the following factors: environmental conditions (temperature, humidity, wind speed and radiation), clothing, body surface and sweat rate.

After sum up all the factors that can influence skin temperature, it is easy to understand why skin temperature does not always follow the same pattern. Other factors that could affect skin temperature (e.g., circadian rhythm) are explained in the Chap. 3 of this book.

To develop this section, it was decided to conduct a review of the effect of exercise on skin temperature in the different studies, taking into account some of the above factors. The overview of the studies is shown in Table 5.1. In particular, the Table aims to summarize the studies assessing both the magnitude and the direction of skin temperature changes in response to exercise with respect to basal pre-exercise condition. Ten studies were selected using the following criteria in order to present the last and most representative researches: (1) published after 2005, (2) more than 10 participants, (3) ROIs excluding foot and hands for its particular physiology, (4) published in international peer-reviewed journals and written in English, and (5) avoid repetitive characteristics. The last criteria means that if there are some studies with different objectives but with similar experimental conditions, only one study was selected (i.e., the study with the higher number of participants). An example of this criterion are the studies performed by Priego Quesada and colleagues [16, 30, 53, 54] where the objectives are different but in all of them the characteristics of the exercise (45 min of moderate cycling) and environmental conditions are the same.

After review the Table 5.1, it is possible to extract some ideas:

- The environmental temperature ranges from ~ 20 to ~ 25 °C, with relative humidity from 45 to 63%.
- Skin temperature response to exercise has been investigated following cycling or running exercises, sports game activities and resistance exercises. In cycling and running exercise, it is worth distinguishing between constant load submaximal exercise [16], and incremental maximal exercise until exhaustion [40, 41].
- The different studies suggested that there are differences in the skin temperature response between the ROIs analysed. As previously was mentioned, skin temperature in specific regions of the body is the result of a thermal balance between muscle activity, vasodilation and sweat evaporation [3, 24, 54].
- The studies that assessed stable load submaximal exercise [28, 54, 55] showed a skin temperature increment of active muscle. Although it is difficult to affirm that skin temperature of active muscles increases in constant exercise, it is

Table 5.1 Overview of some of the most representative IRT studies in sport and exercise physiology

No.	Study	Participants characteristics	Environmental conditions	Exercise characteristics	Result Δ Skin temperature
<i>Stable workload</i>					
1	de Andrade Fernandes et al. [28]	12 males physically active	25 ± 1 °C, 62 \pm 6%	Running. 12 blocks of 5 min each at the 60% of the $\dot{V}O_{2\max}$ separated by an interval of 1 min	Mean skin temperature: \sim \downarrow 0.5 °C Arm: not changes Thigh: \sim \downarrow 0.5 °C
2	Priego Quesada et al. [55]	29 males runners and 15 females runners	24 \pm 1°C, 49 \pm 11%	Running, 10 min warm up and 20 min at 75% maximal aerobic speed (aerobic high intensity)	Knee extensors: \sim \uparrow 1 °C Knee: \sim \uparrow 2 °C Anterior ankle: \sim \uparrow 1.5 °C Achilles: \sim \uparrow 3 °C Rest of lower limb ROIs: not changes
3	Priego Quesada et al. [54]	19 males trained cyclists	24 \pm 1 °C, 45 \pm 12%	Cycling, 45 min at 50% peak power	Knee extensors: \sim \uparrow 1 °C Rest of body ROIs (trunk and lower limbs): not changes
<i>Incremental workload</i>					
4	Merla et al. [40]	15 males trained runners	23–24 °C, 50 \pm 5%	Running, incremental test until exhaustion	Trunk: \sim \downarrow 2 °C Forearm: \sim \downarrow 4 °C Thigh: \sim \downarrow 5 °C
5	Abate et al. [56]	20 trained runners and 20 sedentary males	23 \pm 1 °C, 55 \pm 10%	Cycling. Three steps: 5 min at 100 W, 5 min at 130 W and 5 min at 160 W	Trunk: \downarrow \sim 0.9 °C trained Not changes untrained Upper limbs: \downarrow \sim 0.8 °C trained Not changes untrained
6	Arfaoui et al. [57]	11 male cyclists	20 \pm 1 °C	Cycling, incremental test during 18 min until 250 W	Gastrocnemius: \downarrow \sim 1 °C
7	Priego Quesada et al. [41]	10 males physically active	20 \pm 1 °C, 63 \pm 3%	Cycling, incremental test until exhaustion	Knee extensors: \sim \uparrow 1.5 °C Biceps femoris/gastrocnemius medialis: not changes

(continued)

Table 5.1 (continued)

No.	Study	Participants characteristics	Environmental conditions	Exercise characteristics	Result Δ Skin temperature
<i>Training game session</i>					
8	Chudecka and Lubkowska [23]	16 professional males handball players	20 °C training and 25 °C thermography room, 55%	Training session 90 min: endurance training and handball game	Upper extremities: \sim \downarrow 2.4 °C
<i>Resistance exercise</i>					
9	Ferreira et al. [37]	14 elderly and 15 young	22–24 °C, <50%	Resistance exercise. One limb 3 min knee extension and flexion with a 1 kg weight.	Posterior thigh exercised limb: not changes Posterior thigh contralateral rest limb: \sim \downarrow 0.5 °C
10	Formenti et al. [38]	7 trained and 7 untrained females	22–23 °C, 60 \pm 5%	Resistance exercise with body weight, 2 min standing calf raise.	Calves: \sim \uparrow 1.0 °C trained \sim \uparrow 0.4 °C untrained

possible to suggest that in this kind of exercise the heat production of this area is higher than no active muscles, showing larger increases or lower decreases of skin temperature during exercise.

- There are discrepancies in skin temperature response between the different studies. For example, in the study by Merla and colleagues [30], an incremental maximal exercise [40] induced a large decrease in skin temperature of active muscles during running, whereas incremental maximal cycling exercise tested by Priego Quesada et al. [41] induced an increase. Differences between the two exercises could be related with the kind of exercise (running vs. cycling). However, it is important to remind that other factors could affected these differences: duration of the exercise, environmental differences (i.e. differences in relative humidity), differences between participants in fitness level, age, body composition, etc.
- Resistance exercise with body weight studied by Formenti et al. [38] induced an increase in skin temperature of the calf area. Conversely, resistance exercise with very low load (i.e., 1 kg) studied by Ferreira et al. [37] did not produce any modifications on active muscles. Resistance exercises may have a lower sweat production (in some cases non-existent). This could result in a direct association between intensity of exercise and skin temperature response, contrary to what happens to other exercises (e.g., cycling and running) that result in a whole body sweating. However, further studies are necessary to research this idea.

All in all, there is a large heterogeneity in the methodology used, that depends also on the purpose of the study. Differences can be found in the sample characteristics, exercise characteristics, as well as region of interests considered. Due to this heterogeneity, it is generally difficult to find a common point among the studies.

5.5 Relationship Between Skin Temperature and Performance Variables

Most of the studies that have investigated the skin temperature modifications associated to exercise by IRT have focused on identifying possible relationships between skin temperature values and performance parameters. Among them, the performance variables most studied are undoubtedly cardiorespiratory parameters, such as maximal oxygen uptake (VO_{2max}) and heart rate.

The relationship of skin temperature changes with cardiorespiratory parameters associated to exercise have been studied both during team sport training [23], endurance cycling exercise [57], and resistance exercise [58]. Chudecka and Lubkowska [23] published a study aimed to investigate the temperature changes in arms and forearms in response to a 90 min physical exercise session. Furthermore, the authors investigated also the impact of physiological factors (such as VO_{2max} and heart rate) on the dynamics of temperature changes. Sixteen professional handball players performed a training session lasting 90 min, which contained elements of the actual game, such as sport specific plays. The session was

performed in a sports hall with air temperature of 20 °C and air humidity of 55%, i.e., thermal neutral environment. The skin temperatures of arms and forearms were registered before, immediately after and 10 min after the training session. They obtained a regression model with a significant correlation when the participants with a higher fitness level (by VO_{2max}), higher percentage of the maximum heart rate during the training season, and lower skin-fat fold on the arm, presented a higher decrease in skin temperatures after exercise. The reduction in the skin temperature after the training session was primarily attributed to the efficacy of sweat evaporation mechanism. The authors concluded stressing that players with higher fitness level (VO_{2max} and lower fat body composition) may be beneficial by better thermoregulatory response. Furthermore, a possible explanation regarding the higher decrease in skin temperature in players with a higher percentage of the maximum heart rate was that these players exercised with greater intensity, thus probably sweating more. This in turn implicates a more efficient heat elimination, and of consequence larger decrease in skin temperature after the end of the training session [23].

If Chudecka and Lubkowska [23] investigated the relationship between performance variables and skin temperature after an handball training session, another research group published two studies investigating such relationship in cycling exercise [57, 59]. In the more recent study, Arfaoui et al. [57] investigated the relationship of skin temperature of gastrocnemius with heart rate during an incremental cycling exercise. Eleven subjects performed an incremental cycling exercise on a cycle ergometer. The exercise began at a power output of 100 W (10 min), and then the intensity increased in increments of 50 W every 3 min, each up to 200 W, whereas the last load was performed at 250 W for 2 min. Skin temperature (measured by infrared thermography) and heart rate were recorded continuously during the experiment. Skin temperature values at each stage of the exercise were reported as variations with respect to basal values. Dynamics of skin temperature and heart rate during exercise are reported in Fig. 5.6. Immediately at the onset of the exercise, skin temperature of the calves drastically decreased. This rapid fall in skin temperature during initial stage of the exercise was not attributed to increased evaporative cooling but to vasoconstriction related to the muscular blood recruitment [6]. This phase was followed by a steady state period, thus meaning the presence of a thermal equilibrium between heat production and heat dissipation reflected on the skin. Prolonging exercise increased the metabolic heat production thus invoking thermoregulatory processes. In fact, an important decrease in the skin temperature occurred as exercise intensity increased (i.e., from 150 W at each load). Heart rate showed a quasi-perfect reverse dynamic with respect to skin temperature, thus proving the presence of a strong relationship between the two variables. This was also confirmed by the significant correlations found by the authors between heart rate and the skin temperature variations during the phase of 100 W ($r = 0.9$), and the incremental phase until 250 W ($r = 0.99$).

The relationship between skin temperature and heart rate was also investigated and assessed during resistance exercise. Neves et al. [58] studied the association between the skin temperature change and the heart rate response during two

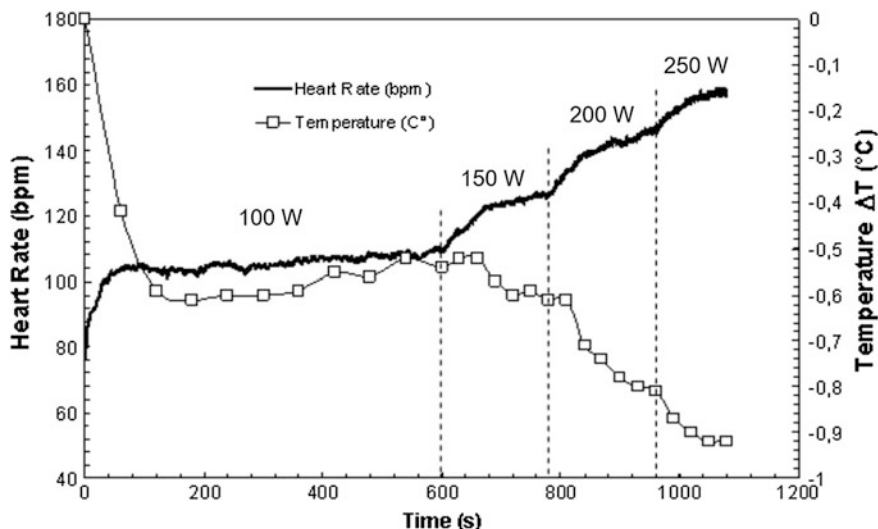


Fig. 5.6 Heart rate and skin average temperature gradient during incremental cycling test. Figure modified from Arfaoui et al. [57]

sessions of resistance exercises at different intensities. A sample of 31 female subjects were divided in two groups: 15 subjects performing unilateral biceps curl, and 16 subjects back half squat at 90° . The exercise protocol of both biceps curl and squat was repeated in two randomized sessions (70% of 10 RM and 80% of 10 RM). The exercise protocol consisted in four sets with 10 repetitions in each set, and with 30 s to rest between them. The heart rate and skin temperature in the two groups were recorded continuously before, during and after exercise. Skin temperature on the active muscles decreased during exercise and during the first minutes of the recovery period, returning to basal values within one hour of recovery after exercise. There were no statistical differences in thermal response to exercises in 70 and 85% of 10 RM in both biceps curl and squat group. Significant negative correlations between heart rate and skin temperature during exercise were found in the 70% of 10 RM session only in the squat group, whereas in the 85% of 10 RM session both in the biceps curl and squat group. Moreover, significant negative correlations were also found in the recovery in the 70 and 85% of 10 RM, both in the biceps curl and squat group. The authors concluded stressing that skin temperature on the active muscles decreased during exercise and during the first minutes of the recovery, returning to basal values slowly.

Infrared thermography have been also used to assess the difference in thermoregulation between subjects with different level of physical fitness [38, 56, 60]. Based on the fact that higher fitness level is associated with higher skin blood flow during exercise [61], Merla et al. [60] conducted an experiment aimed to compare the skin temperature response to an incremental cycling exercise between trained and untrained subjects. After an initial trend that was similar in both groups, trained

subjects exhibited a higher decreasing temperature rate with respect to the untrained ones. These findings seem to support the hypothesis that the muscular capability to recruit blood to supply its needs during an exercise is better in trained subjects than in untrained ones [60].

Further evidences in this direction have been more recently provided by the studies by Abate et al. [56] and by Formenti et al. [38]. In these studies, the authors investigated the influence of physical fitness on exercise-associated skin temperature changes. It was hypothesized that exercise can induce differences in the trends of skin temperature between trained and untrained subjects. As regards to the study by Formenti and colleagues [38], 7 trained and 7 untrained female subjects performed standing calf rise exercise lasting 2 min, with a constant pace consisting in 1 s eccentric and 1 s concentric phase, with the aim of a metronome. Skin temperature of the calves were measured before, during, and for 7 min after the exercise. By comparing the parameters describing the skin temperature time course in two groups, it was found that trained subjects, after a slightly decrease due to vasoconstriction recruiting blood flow to the active muscles, increased their skin temperature differently with respect to untrained subjects. Specifically, trained subjects responded to exercise more quickly than untrained controls.

Also the study by Abate et al. [56] supports the findings by Formenti et al. [38]. In this study [56], the authors investigated the differences in the cutaneous temperature among trained and untrained subjects. 20 trained and 20 untrained male subjects performed a standard cycling warm up, divided in three steps: (1) 0–5 min at 100 W; (2) 5–10 min at 130 W; and (3) 10–15 min at 160 W. Thermal images of thorax and upper limbs were recorded during the exercise. With respect to baseline, trained subjects exhibited a significant temperature decrement in the third step in both trunk and upper limbs, while no difference was observed in untrained subjects. In the comparison between groups, a statistically significant difference was observed in both regions of interest (i.e., trunk and upper limbs), in the second and in the third step. In conclusion, the findings of these study support the notion that the level of physical fitness improves the ability to rapidly activate thermoregulatory processes in response to exercise [38, 56].

Since surface electromyography permits to estimate the magnitude of electrical neuromuscular activity during exercise, it was also hypothesized the existence of a relationship between muscle activation during exercise and associated-skin temperature modifications [41, 62]. The study by Bartuzi was probably the first assessing this relationship [62]. It was observed an inverse relationship between biceps brachii activation and skin temperature during fatigue isometric contractions. Based on these findings on isometric exercise, another group of research investigated the relationship between neuromuscular activation (measured using surface electromyography) and skin temperature of different body area (measured using infrared thermography) during an incremental exercise on a cycle ergometer [41]. Subjects performed an incremental cycling test until exhaustion on a cycle ergometer. The incremental cycling test started with initial workload of 50 W lasting 3 min, and it was followed by increments of 25 W/min until reaching the complete exhaustion. Pedaling cadence was controlled at 90 ± 3 rpm. Peak power

output was identified as the workload of the last stage. Skin temperature of front and back surface of subjects' thighs was recorded in three different times during the experiment. Neuromuscular activation was monitored using surface EMG from the right and left rectus femoris, vastus lateralis, biceps femoris and gastrocnemius medialis throughout the duration of the test. No significant correlations between skin temperature and neuromuscular activation were found in rectus femoris, biceps femoris and gastrocnemius medialis. In fact, the relationship observed was in vastus lateralis, and it was more related with fitness level and not with the heat generated by the muscle. Participants with higher overall neuromuscular activation and lower frequency content in activation for vastus lateralis presented lower increments of skin temperature, or what is the same, better thermoregulatory response. This profile of neuromuscular activations was associated with better fitness level.

Finally, it is important to remark the association between fat composition and skin temperature. Priego Quesada et al. [41] observed that participants with larger thigh skinfolds presented lower increments of skin temperature in ROIs of the thigh ($p < 0.01$ and $r > -0.7$). These authors discussed two points about this association. Firstly, it is clear that body fat tissue had an insulation capacity resulting in impairment of the heat dissipation between the core and the skin [23, 63, 64]. Moreover, it is worth considering that fat tissue is related to the physical fitness [65]. Body composition is one of the factors that change with the training and this variable can be one of the factors that explain the differences between people with different fitness capacity. On the other hand, Chudecka and Lubkowska [23] selected this ROI in their study in relation with the fat tissue composition. They suggested that upper limbs are appropriate ROIs to analyze the effect of a training session for its lower adipose tissue and then less effective thermal insulation.

5.6 Conclusion

In this chapter we presented a general overview on the literature about the study of the skin temperature response to exercise assessed by means of IRT and its relationship with other thermoregulatory variables, exercise characteristics and performance factors. Some conclusions could be extracted from the chapter:

- IRT presents some differences in the skin temperature calculation in comparison with the thermal contact sensors, and also some advantages and limitations. Generally, IRT presents lower values of skin temperature during exercise than thermal contact sensors. Furthermore, IRT could provide the measurement of large areas without interfere in the heat exchange of the subject. However, it is not possible to measure when the subjects are clothed and the sweat could interfere in the temperature calculation. This advantages and limitations are important to take into account before and after a study.

- The experimental approach (e.g., measure during exercise or before-after exercise) and the characteristics of the exercise will influence the skin temperature, and researchers should be aware in the design of the experiment.
- Skin temperature is the result of different thermoregulatory variables such as blood flow, sweat rate and core temperature. It is important to know the role of all these variables in order to interpret correctly the skin temperature changes.
- Differences in skin temperature response to exercise between studies in the literature are due to heterogeneity in exercise characteristics, as well as region of interests considered.
- People with better physical fitness presents a more effective thermoregulatory system or, what is the same, a greater capacity of heat dissipation. Because of this, different studies have observed relationships between some performance parameters and skin temperature.

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