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Review

Classification of factors influencing the use of infrared thermography in humans: A review

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HIGHLIGHTS

- The number of the factors that affect the skin temperature (Tsk) in humans is tremendously large.
- This review proposes a comprehensive classification in three primary groups: environmental, individual and technical factors.
- Further research is necessary to delimit the unspecified influence of most of the factors and to improve this classification.

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ABSTRACT

Body temperature is one of the most commonly used indicators of health status in humans. Infrared thermography (IRT) is a safe, non-invasive and low-cost technique that allows for the rapid and non-invasive recording of radiating energy that is released from the body. IRT measures this radiation, directly related to skin temperature (Tsk) and has been widely used since the early 1960s in different areas. Recent technical advances in infrared cameras have made new human applications of IRT (beyond diagnostic techniques) possible. This review focuses on the lack of comprehensive information about the factors influencing the use of IRT in humans, and proposes a comprehensive classification in three primary groups: environmental, individual and technical factors. We aim: to propose a common framework for further investigations; to reinforce the accuracy of human IRT; to summarise and discuss the results from the studies carried out on each factor and to identify areas requiring further research to determine their effects on human IRT.

Contents

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1. Introduction

Infrared thermography (IRT) is a safe, non-invasive and low-cost technique that allows for the rapid and non-invasive recording of radiating energy that is released from the body [1–3]. IRT measures this radiation, directly related to skin temperature (Tsk). IRT has been widely used since the early 1960s in different areas. During the first decades after its development, research into the use of IRT in humans was mainly focused on its applications as a diagnostic tool. However, IRT was replaced by newer and more accurate technologies (such as X-rays and magnetic resonance imaging). Recent technical advances in infrared cameras have made new human applications of IRT (beyond diagnostic techniques) possible.

Since infrared cameras generate thermal images by electromagnetic waves, we should take into account that the laws of optics are applicable for image creation [4–6]. Likewise, as the source of infrared radiation is heat energy, temperature and heat exchange, the laws of thermodynamics must be mentioned and outlined [5,7,8].

Working with IRT requires accounting for many factors that can influence either the evaluation or the interpretation of the thermal images [9]. Attempting to control for such a large number of factors may seem impossible, but simply being acquainted with these factors is an important step in many contexts. Therefore, the primary objective of this article is to propose a classification of the factors that influence the application of IRT in humans.

2. Methods

Medline, Pubmed, ISI Web of Knowledge, Ingenio, Science Direct, EBESCO, Springerlink, IEEE Xplore and Google Scholar were used as search engines to identify studies related with infrared thermography and all that influence factors. Due to the huge list of keywords, there was not a unique "search sentence", but a combination between the common keyword of "infrared thermography or thermal imaging or thermology or infrared or

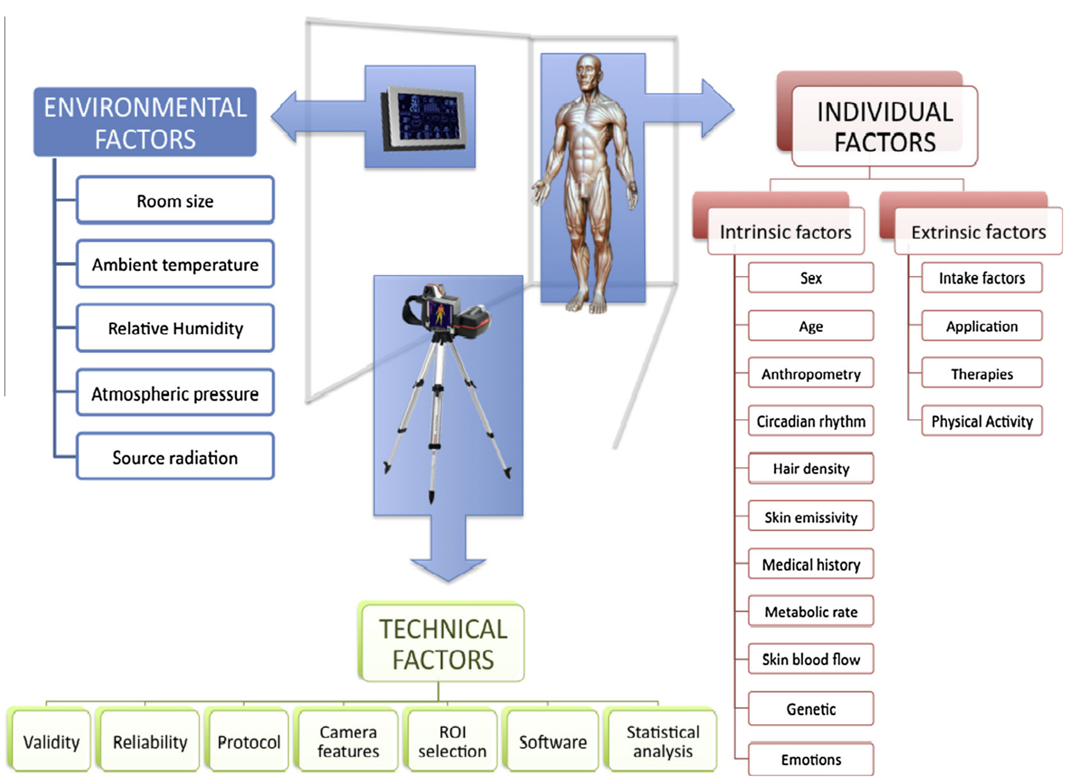

Fig. 1. Representation of the classification of IRT-related factors in humans.

thermometry or thermovision or IR imaging or thermal video" and list of influence factors keywords, as for example "humidity", "alcohol", "injuries", etc.

Because of the technological improvement of IRT in the last years, original papers published in the last 20 years were preferentially considered. The inclusion criteria for study selection were (1) the literature was written in English, (2) participants were human beings, and (3) Skin temperature assessed by (non-contact) infrared thermography. Potentially relevant studies were also included by reviewing some bibliographies on infrared thermography [10–17] and the references from the found articles, which may have been missed in the original search.

3. Classification of influence factors

These factors will be divided into three primary groups (see Fig. 1):

- *Environmental factors:* Those that are related to the place where the evaluation is performed.
- *Individual factors:* Those that are related to the subject being assessed and his/her personal characteristics that could influence skin temperature (Tsk). These factors will be divided into intrinsic and extrinsic factors.
- *Technical factors:* Factors that are linked to the equipment used during the IRT evaluation.

3.1. Environmental factors

The first group of factors are those related to the natural characteristics of the environment where the IRT evaluation is performed. Environmental factors are very important and, unlike individual factors, are more controllable.

3.1.1. Room size

The room itself is not a significantly influential factor; however, it must meet certain basic requirements to remain a neutral location. The cubicle should be sufficiently large to house the evaluation equipment and the patient and to maintain a homogeneous temperature in the entire room. The minimal room size recommendation is 2×3 m, but a larger room is desirable [3,18]. Likewise, rooms with high ceilings are not recommended because of the difficulty of maintaining a homogenous ambient temperature in the room.

3.1.2. Ambient temperature

The ambient temperature is very important for most human IRT applications [19–22]. The majority of references suggest a temperature range of 18–25 °C (see Table 3), because the subject is likely to shiver in lower temperatures and to sweat at higher temperatures [3,18,23–25].

Certain authors have described Tsk variations at different ambient temperatures [26–31]. Specifically, Ring and Ammer [3] explained that there is an ideal ambient temperature depending on the aim of the examination. A warmer ambient temperature (from 22 °C to 24 °C) is recommended for the evaluation of the extremities. This is due to the influence of the sympathetic nervous system and the tendency of extremities to have lower Tsk in low ambient temperatures. In contrast, inflammatory lesions are easily localised in cool conditions (below 20 °C) [32]. Garagiola and Giani [33] described 21 °C as the perfect ambient temperature, as it is the temperature at which the infrared emission values of the skin are the highest.

Nevertheless, recent studies of IRT have described a strong correlation between the skin and ambient temperature, leading to the possibility of normalising Tsk using a regression formula regardless of the ambient temperature [34]. These results are similar to those that are given by the mathematical model that was developed by Deng and Liu [35] and are consistent with the results of the experiment of Pascoe and Fisher [29], in which the Tsk was observed to increase proportionally with the ambient temperature [35]. A consensus on this issue should be reached in this regard to establish an appropriate correction formula for standardising temperatures that are measured under extreme environmental conditions.

Finally, another matter that is related to ambient temperature is the acclimatisation or equilibration period (see Table 1). The time that is required to reach an adequate stability in Tsk is set at approximately 15′ [23]. Nevertheless, different equilibration periods are used throughout the literature when using IRT, ranging from 10′ [36,37], 15′ [38], 20′ [39–41] to 30′ [42,43] or even 60′ [27]. Following 30 min of acclimatisation, Tsk can oscillate, resulting in thermal asymmetries between the left and the right sides of the body [44].

Hart and Owens [58] performed an interesting investigation in which a constant decrease in Tsk was observed over 31 min of acclimatisation, with stabilisation in the patterns being observed after 16 min. Nevertheless, there was a great deal of variation among the participants, and the authors analysed only paraspinal

Table 1
Experimental conditions used by several authors (based on Lahiri et al. [45]).

Authors	Year	Study	Experimental conditions	
			Ambient temperature (°C)	Acclimatisation time (min)
Chudecka and Lubkowska [41]	2015	Thermal maps of young	25	20
Akimov and Son'kin [36]	2011	Lactate threshold	21–22	10
Kolosovas-Machuca and Gonzalez [46]	2011	Distribution in children	22 ± 1	15
Bagavathiappan et al. [32]	2010	Diabetic neuropathy	25	5
Merla et al. [47]	2010	Graded exercise in runners	23–24	20
Hildebrandt et al. [48]	2010	Sports medicine	21.5–22.3	20
Bouzida et al. [49]	2009	Thermoregulation	24 ± 2	10
Savastano et al. [50]	2009	Adiposity	23.1 ± 0.2	20
Zaproudina et al. [38]	2006	Low back pain	23–25	15
IACT [23]	2002	Guidelines	18–23	15
Ammer [51]	2002	Manual examination	24	15
Ring and Ammer [3]	2000	Guidelines	18–25	10–30
Gratt and Anbar [52]	1998	Facial telethermography	21–23	15
Uematsu et al. [53]	1988	Thermal asymmetry	23–26	20
Devereaux et al. [54]	1985	Rheumatoid arthritis	20.5 ± 0.5	15
Nickoloff [55]	1984	Cervical spine standards	20	10
Gershon-Cohen and Haberman [56]	1968	Thermography of smoking	24	15
Brånemark et al. [57]	1967	Subjects with diabetes	18–20	15–20

Tsk. Due to this lack of consensus, Fisher et al. [28] performed a study demonstrating that extreme environmental conditions can significantly affect Tsk, with 15 min of acclimatisation being insufficient, as the majority of references suggest. Despite these findings, Roy and his team [59] recommend acclimatisation for a minimum 8-min period, followed by an 8-min maximum recording period.

A recent study by Bouzas Marins and collaborators [60] has directly analysed the optimal acclimatisation time for IRT evaluation in humans. They concluded that the optimal period is variable in young men and women, but the minimum acclimatisation period must be 10 min.

3.1.3. Relative humidity

The effects of Relative Humidity (RH) on skin have been previously described [61]. Although RH is commonly reported in studies of IRT in humans, authors have rarely provided a justification for controlling for this parameter. IACT recommends controlling humidity [23], and Amalu et al. [62], specified that RH should be controlled to prevent shivering or perspiring; however, neither of these studies specified a range. In the literature, the majority of studies have been performed between 40% and 70% RH [38,39,47,53,63–66].

RH can influence IRT evaluation in two ways: first, the particles of steam have a (minimal) potential to emit infrared emissions [23]; secondly, there is a direct effect of relative humidity on Tsk.

Authors such as Pascoe and Fisher [29] described a very strong relationship between the ambient temperature and RH, and Deng and Liu [35] explained it using mathematical modelling. Atmaca and Yigit [67] investigated RH's effects on skin temperature and demonstrated that RH did not significantly influence skin temperature if the ambient temperature was maintained within an acceptable range of thermal comfort. Likewise, the results of Gómez Carmona in Spain indicated a poor correlation [34]. Further investigations into the isolated effect of humidity on Tsk should be performed to define a definite range and to describe the specific skin responses to different relative humidity levels.

3.1.4. Atmospheric pressure

Although it is related to ambient temperature and relative humidity, atmospheric pressure is often ignored in the majority of references. Gómez Carmona [34] examined the correlation between these three factors and Tsk (as measured with IRT), identifying ambient temperature as the most significant factor ($r = 0.96$) and humidity as a less significant factor ($r = 0.05$). Surprisingly, the authors observed a significant influence of atmospheric pressure on Tsk ($r = 0.54$) in the 730 IRT images that were analysed. Further investigation is required to identify the ideal range of atmospheric pressure under which to evaluate humans using IRT.

3.1.5. Source radiation

In addition to the room size requirements, several guidelines have noted the importance of isolating the room from any source of infrared radiation [23]. As potential sources of radiation, we can mention: incident lightning, existence of windows (blinded or not), airflow (since it is recommended to have an air control system), heating ducts, water pipes, walls thermal reflectance and room insulation. It is even suggested that the data collection room be carpeted or contain a well-insulated area rug. Providing a background of non-reflective materials is also very important to avoid any reflection source [48].

3.2. Individual factors

As we described in the preceding section, it is possible to control environmental factors if a standardised protocol is followed. Nevertheless, the number of factors concerning the individual is so large, and the factors themselves are so complex, that attempting to control them all is currently impossible. We have no doubt, however, that further investigations will eventually make controlling these factors feasible. For now, it is necessary to list the important factors appears in order to take them into account.

We will establish a division within this group: first, we propose factors that are referred to as "intrinsic" factors, which encompass the nature or long-term state of the individual; we will also consider "extrinsic" factors, which are temporal and external and which are normally related to the personal habits or the daily activity of the subjects.

When evaluating an individual using IRT, we strongly recommend that all of the factors that are listed below be noted. Some of these factors are obvious, such as gender, skin humidity or hair density. However, the majority are cryptic and can influence Tsk and thus the utility of IRT. One of the primary aims of this classification is to make thermographic professionals aware of the importance of constructing their own questionnaire to take into account all possible factors, even those that may have been forgotten here. The acclimatisation period may provide the perfect moment to survey the subject.

3.2.1. Intrinsic factors

Intrinsic factors are the basic characteristics of the subject and are primarily related to biological and anatomical parameters. The available literature on this topic is limited, and more thorough investigations are recommended to determine the influence of these factors on Tsk [68].

3.2.1.1. Sex. Sex may influence the Tsk pattern [69]. Higher tympanic temperatures were demonstrated for women [70], and a higher upper body Tsk was also reported for women [41,71]. In addition, intestinal, rectal, pectoral and hand temperatures were higher for females [72]. However, the reasons for these thermal differences between men and women are unclear [73]. Three primary reasons could be responsible for the observed gender differences in Tsk: the menstrual cycle, subcutaneous fat and the metabolic rate.

Many studies have examined the influence of the menstrual cycle on body temperature [73–76], but fewer have analysed the influence of these factors on Tsk [77], and even fewer have used thermography. The differences between the luteal (warmer temperatures) and follicular phase (colder temperatures) in women relative to men is well established [73] (see Fig. 2). Nevertheless, no differences were observed in vascular or autonomic nervous system reactivity during the menstrual cycle [78]. Following menopause, the thermoregulatory control of the skin's blood flow may be reduced [79].

Much has also been published regarding the relationship of subcutaneous fat and the Tsk differences between men and women. Hardy and Du Bois [69] stated that women have a "thicker layer of insulation against cold" and asserted that women have a physiological advantage compared to men. This conclusion was based on females' better adaptation to warmer environments, larger thermal comfort zone and higher sweating thresholds. In contrast, a study by Karki et al. [80] describes thermal gender differences following a knee washout as due to the tendency for women to have higher fat percentages, thus being more insulated and able to maintain warmer temperatures following cold stimulation. Chudecka et al. [81] found a negative correlation between BMI and Tsk in several body areas (abdominal, hand and thigh areas) in obese women,

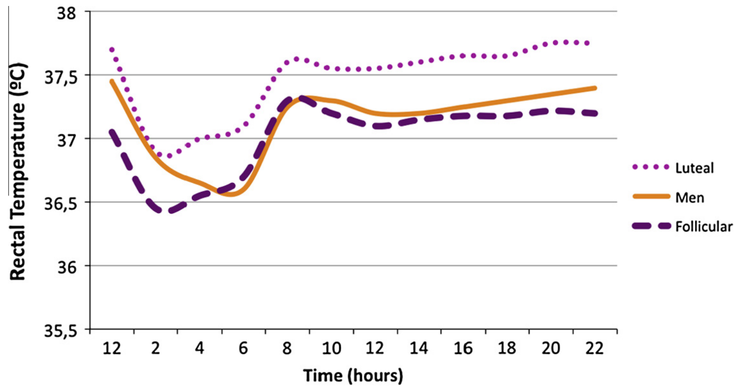

Fig. 2. Tendencies in rectal temperatures between women in the luteal and follicular phases and men (adapted from Baker et al. [73]).

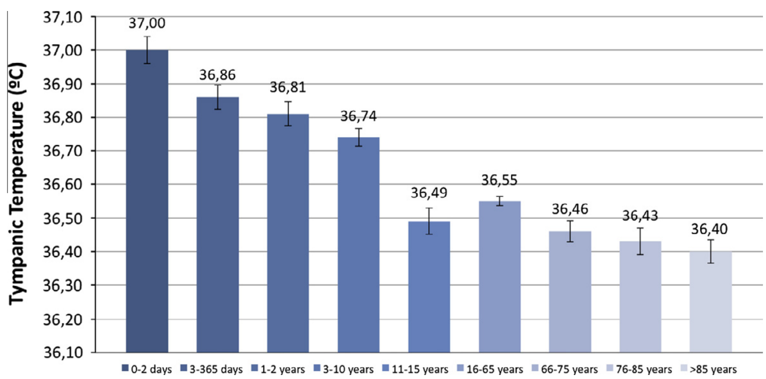

Fig. 3. Evolution of human tympanic temperature (adapted from Chamberlain et al. [70]).

but also in normal-weight young women and men (chest, upper back, abdomen, lower back) [41].

Recently, Fournet et al. [82,83] described Tsk differences only in the thigh between males and females due to local body fat (up to 2 °C colder in women before exercise). The authors concluded that the lower overall mean Tsk values of females were not due to subcutaneous fat but to the metabolic rate. More locally, Christensen and his team [84] analysed gender differences in facial skin temperature, finding a higher facial Tsk in males, and identified blood circulation and metabolic rate as the main reason for this difference.

Therefore, the metabolic rate also plays an important role in explaining gender differences in Tsk. This effect has been described by several authors [69,85,86], but none of these studies used IRT to measure Tsk, and the studies were generally conducted under extreme conditions. In addition to these three factors, other studies using IRT, such as one conducted by Haas et al. [87], have demonstrated that males exhibit a more rapid rewarming period in local (hand) thermal regulation following cold stimulation. This effect may be due to a theoretically more prevalent vasodilatation reflex in men.

In conclusion, it appears that gender may influence the results of IRT in humans. Despite contradictory results, such as Zaproudina's [88], that indicated non-significant gender-related differences in Tsk, more research into this topic, using IRT as a tool for Tsk assessment, is necessary.

3.2.1.2. Age. It appears clear that temperature and age are related; however, it is unknown how strong this relationship is and the manner in which Tsk is affected by age. Several references were found for this topic that provide different perspectives.

One of the most interesting and graphic descriptions of the evolution of temperature over time is a study that was conducted by Chamberlain et al. [70]. These authors demonstrated, using a sample of 2447 subjects of different age groups, how tympanic temperatures decrease in the elderly, with a very large decrease being observed between birth and 15 years of age (see Fig. 3). Niu et al. [89] described a slightly lower Tsk in elderly than in young subjects in a normative IRT study of subjects in Taiwan.

Decreases in temperature with age may be related to a lower metabolic rate and to a decrease in heat dissipation abilities [90]. Symonds and collaborators [91] showed age-related changes in Tsk within the supraclavicular region that were related to brown fat in healthy children. An age-related impairment in vasoconstriction and vasodilation has been documented, as has a reduction in the activity of skin sympathetic nerves [92,93]. Weinert [94] also described the manner in which the circadian rhythm changes with age.

Tsk has been studied in several age groups, including neonates. IRT appears to be a promising tool for assessing neonatal control of normal Tsk and adaptation to the new environmental conditions following birth [95–98]. A recent study of a sample of Mexican children indicates decreased Tsk variability at young ages [46]. However, it appears that a long period of Tsk stability begins following puberty, with no significant changes until an advanced age. Therefore, Zaproudina [88] did not find age to be a factor in their studies of subjects who were between 18 and 28 years of age.

Two investigations of IRT comparing young (approximately 23 years of age) and elderly (over 60 years of age) individuals have described important age differences (up to 1 °C) in the temperatures of the hands, feet [99] and limbs [64], with lower temperatures always being reported in the elderly group. Ferreira et al. [64] observed less rapid heat dissipation in the limbs in the elderly following exercise; in contrast, Rasmussen and Mercer [99] described a slower rewarming process in elderly individuals after local cooling of the hands and feet.

In summary, Tsk is slightly lower in elderly subjects, particularly in distal body areas [53,64,89,100]. However, this is certainly an important area of research that needs more data [81,101].

3.2.1.3. Anthropometry. The problem created by a classification of anatomical parameters is the strong relation between these parameters. Here, we will discuss factors related to individual anatomy, dividing these factors into two groups: factors that concern weight and those that are related to the subject's height. Clearly, the correlations between these and the above factors, such as gender, are strong; however, our aim is to evaluate the independent influences of these anatomical factors.

3.2.1.3.1. Height. Little has been written on the influence of human height on Tsk. Havenith [86] explained the role of human surface area on body temperature in a review: "*Heat loss is proportional to the gradient between skin and environment, [...] and to the surface area available for heat exchange [...] and thus a high body surface-to-mass ratio would provide a high heat loss surface area relative to the heat production volume. In effect, this implies that smaller people (i.e., females) should be at an advantage in the heat over bigger people (males)*". However, no study correlated height in cm (regardless of gender) with the Tsk pattern or analysed this relationship more deeply.

3.2.1.3.2. Weight. Weight is directly related to height and to other parameters, such as body mass index (BMI). Therefore, certain conclusions regarding weight may be related to other factors, such as gender or age. However, the most significant factor related to weight may be subcutaneous fat. The thermal insulating property of adipose tissue has been considered one of the most important influences on individual thermal patterns [102].

LeBlanc [103] described that variations in Tsk between different individuals may be due to differences in fat thickness. In an interesting study that used IRT and thermistors, Livingston et al. [27] observed lower Tsk in areas with greater skinfold thicknesses. Furthermore, these authors reported larger Tsk variations among subjects with more body fat at cooler ambient temperatures (18 °C); these variations become lower as the ambient temperature increased (i.e., between 23 °C and 28 °C).

Savastano et al. [50] reported the thermal pattern characteristics of obese subjects under thermoneutral conditions using thermography. These authors explained these results by hypothesising the existence of a thermoregulatory compensation that relates reduced heat loss to high abdominal fat, an effect that would be accompanied by augmented heat dissipation from the hands. Karki et al. [80] suggested that lower temperatures of the knees in women may be due to higher fat percentages, and Chudecka and Lubkowska [41] showed a negative correlation between BMI, percentage of fat (PBF) and Tsk in chest, upper back, abdomen, lower back (both in women and men). In contrast, Fournet et al. [83] examined Tsk in the cold prior to and during exercise, identifying an inverse relation between Tsk and skinfold thickness on the anterior torso, but not on sites on the back. These authors were not able to detect any correlation between body temperature and the sum of all of the thicknesses of the skinfolds that were measured.

Therefore, an inverse relation has been demonstrated between body fat and Tsk, but only in certain body areas. Further investigations are required to increase our knowledge of the thermal pattern of other body areas.

3.2.1.4. Circadian rhythm. The circadian rhythm and its influence on body temperature has been widely researched and described [70,104,105]. Binder et al. [106] and Salisbury et al. [107] both demonstrated higher Tsk in diurnal assessments when using IRT. On the other hand, Bianchi et al. [105], divided their sample into two groups: those who reached the highest Tsk during the morning, and those who reached peak Tsk in the evening. Nevertheless, the peak in most of the ROI analysed by Bianchi and collaborators [105] were during the evening (approximately 18 pm). Ring contributed as well, highlighting that the more stable time for assessing Tsk is before 12 pm (acrophase) in subjects from the UK [108].

A distinction must be made between research performed on the energy dissipation of the body and Tsk. The body's thermoregulation functions as a gradient between the core temperature and Tsk, allowing for heat to be exchanged with the environment by means of convection and radiation [109]. Therefore, the current charts that describe the evolution of rectal, gut or axillary temperatures (core temperatures) [110] should be not taken as representative of what occurs at the level of the skin.

The most interesting findings regarding the circadian rhythm's effect on Tsk were performed by Krauchi and Wirz-Justice [111], who described different Tsk values depending on the area of the body being examined. Proximal Tsk (i.e., the infraclavicular region, the thigh, and the forehead) followed the same circadian rhythm as did the rectal temperature (see Fig. 4). In contrast, distal Tsk (i.e., the hands and the feet) measurements exhibited the opposite pattern [111]. There is no doubt that daily activity directly influences Tsk variations [112]. Nevertheless, further studies with more specific data regarding the daily evolution of Tsk in different body areas will aid in the better understanding of these daily variations.

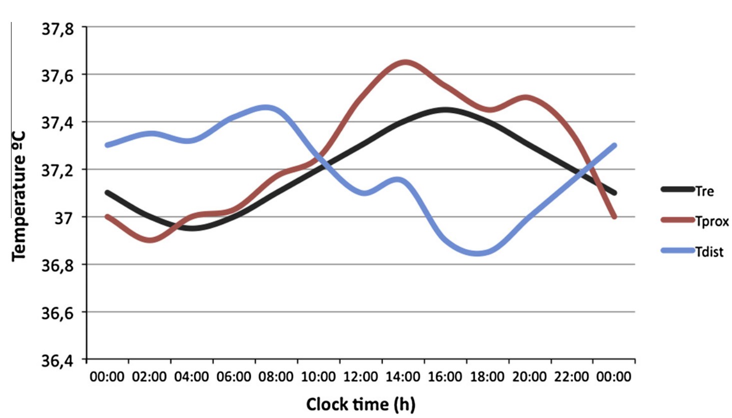

Fig. 4. Smoothed tendencies of circadian rhythm in rectal temperature (Tre) and skin temperature in distal regions (Tdist), including the hand and foot, and proximal regions (Tprox), including the forehead, stomach, infraclavicular region, and thigh (adapted from Krauchi et al. [111] and Reilly and Waterhouse [113]).

Moreover, several authors have examined the best time at which to engage in physical activity, considering the daily skin and body temperatures [114,115]. The majority of these studies agree that improved performances are reached during the evening due to the body's better ability to remove heat loads [116–118].

3.2.1.5. Hair density. When one sees a human thermal image for the first time, one is surprised at the distribution of colours that cover the skin, the background darkness, and the cold temperatures of certain areas, such as the hands or the head. Lower temperature in hair areas is linked to hair emissivity. However, there are few references regarding the potential influence of hair density or length on other body areas.

Barnes [119] described hair as an avascular substance that appears cold on a thermogram, being in thermal equilibrium with the environment. Ng (2009) spoke of the factors that influence skin emissivity, mentioning hair. Uematsu et al. [53] indicated the unpredictability of Tsk on hair-covered areas, and Togawa and Saito [120] described lower values of temperature on body areas with hair. Surprisingly, no guidelines, protocols or studies have analysed differences in Tsk between hair-covered and hairless surfaces. Only Merla et al. [47] and Abate et al. [40] mentioned that study participants were asked to remove their body hair 5–6 days prior to the evaluation in order to obtain the most accurate thermal readings.

Most references regarding the influence of hair have examined animals [121–123]. Clearly, the presence of hair on the human body is not as extensive as in other mammals, but it is interesting to note the potential influence of hair in situations where there is hair on important areas of the skin.

3.2.1.6. Skin emissivity. Skin emissivity is a topic of current study. Since Hardy and Muschenheim [124] wrote the first article on this subject in 1934, many investigations have reported different values of this quantity. However, despite these differences, it is certain that human skin emissivity is very high and constant, nearly like a black body.

Hardy wrote a number of studies in the 1930s that analysed skin emissivity. These studies essentially concluded that human skin emissivity was that of a black body and independent of wavelength [124,125]. Some years later, Barnes [119] indicated that human skin emissivity was 0.99. Steketee [126] published an interesting study that reported that emissivity is nearly constant, with a value of 0.98 ± 0.01. This study also reported that the emissivity of black, white or burnt skin is the same, independent of the nature of the experiments (in vivo or in vitro) and falls within a range of wavelengths (between 2 and 14 μm).

Togawa [127] described very interesting results in his study of skin emissivity, analysing the factors and reasons why a range of results from 0.94 until 0.99 have been obtained for this measure. He suggested that results such as those from Steketee [126] were incorrect in that they underestimated Tsk due to of a temperature gradient on the skin, setting the human Tsk at 0.97.

Of the most recent published works, the one written by Sanchez-Marin et al. [128] is the most relevant. In this study, the authors investigated established a skin emissivity of 0.996 at a wavelength of 10.6 μm.

Despite the time that has passed since the first study by Hardy, a consensus has not been reached regarding the correct value of skin emissivity. Skin colour influences emissivity; however, the differences are thought to be very small [126]. Although further research would be very interesting, it is clear that human skin emissivity ranges between 0.97 and 0.99 at wavelengths of between 2 and 14 μm [127,128]. Therefore, most authors have performed their investigations using 0.98 as the standard skin emissivity value [40,84,129].

3.2.1.7. Medical history. Human skin is the natural protection of the body, a type of biological shield that protects us against environment dangers. In an ideal world, our skin should maintain a constant thermal pattern over time, with the constant aim of keeping the body in thermal balance or "homeothermy". However, continuing with the analogy of the shield, lifelong exposure to many external factors (e.g., solar radiation or scars) leave their marks on human skin, breaking and altering the thermal pattern with permanent hot/cold spots, which could influence the correct interpretation of a thermographic image.

Many studies have been published regarding the thermal responses of Tsk to injuries, diseases or wounds. Surprisingly, fewer studies have been written regarding the effects of these sources on Tsk that remain once the condition is recovered or healed.

Rochcongar and Schmitt [130] published an interesting work describing the effects of different injuries on Tsk and highlighting the potential of IRT to indicate the degree of the lesion and control its evolution. Some years later, Ring [108] described in detail the basic skin responses after an injury as identified by Rochcongar and Schmitt [130]: normothermic, hyperthermic and hypothermic patterns, i.e., increased and decreased temperatures.

In many cases, hyperthermia occurs when inflammation or any other process that leads to higher skin blood flow is present. Therefore, infections [131], tendinitis [132], bursitis, bone fractures (including stress fractures) [133–135], arthritis [54,136–142], tennis elbow [106], acute muscle injuries [143,144], compartment syndrome [145], anterior cruciate ligament surgery patients [146], other surgical applications [147], and other problems that derive from inflammation or trauma have been previously described. Alternatively, hypothermia can occur as a consequence of degenerative processes [99], arterial or vein occlusion (e.g., deep vein thrombosis) [148], nerve damage, reflex sympathetic dystrophy [149,150], Raynaud's phenomenon [151–154], or the presence of avascular tissues from wounds or burns [155–158]. Moreover, other authors described the manner in which pain could cause both hypothermy and hyperthermy [159]. Alterations in skin temperature have also been reported due to diseases such as allergies, brain lesions, cancer, chronic fatigue syndrome, depression, fevers, human immunodeficiency virus (HIV) infection, insomnia, obesity, psoriasis and thyroid dysfunction [160]. Finally, Sillero and collaborators [161] have published a study describing the different Tsk responses of 202 patients admitted to the Emergency Unit at the CEMTRO clinic in Madrid.

However, no differences have been described between the acute and long-term effects of these factors on Tsk. Scars are a good example of a type of skin heterogeneity that can influence Tsk, however they are not commonly described in the literature [119,162–165].

Our experience has shown other examples help to illustrate this point, such as the asymmetries that we have detected following anterior cruciate ligament injuries, where the affected areas maintain persistent asymmetry once the injury is completely healed, even years later (see Fig. 5). The literature also describes the effects of varicose or superficial veins on long-term alterations in Tsk [32,166] (see Fig. 6). It has also been documented that tattoos could lead to a certain degree of thermal pattern alterations [167].

Additionally, Chudecka [168] has recently noted the special characteristics of Tsk in individuals with eating disorders, such as anorexia or bulimia. The author highlighted that one of the symptoms of these disorders could be identified by a state of hypothermia due to starvation, dehydration, slower metabolic processes, hormonal imbalance (decrease of thyroid hormones), disorders of the circulatory system and a significant loss of body fat and muscle [169–173].

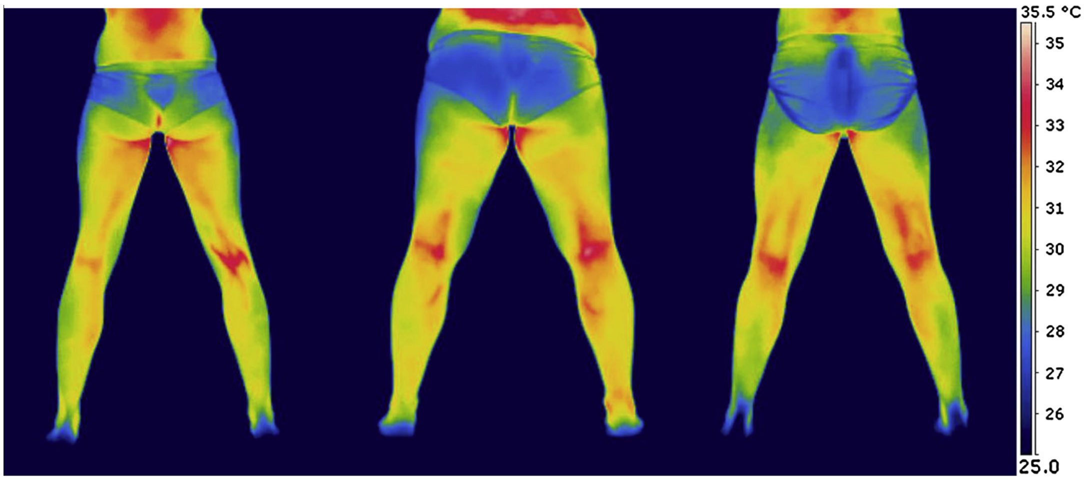

Fig. 5. Subjects 9 months (left), 4 years (centre) and 6 months (right) after anterior cruciate ligament surgery on the right knee.

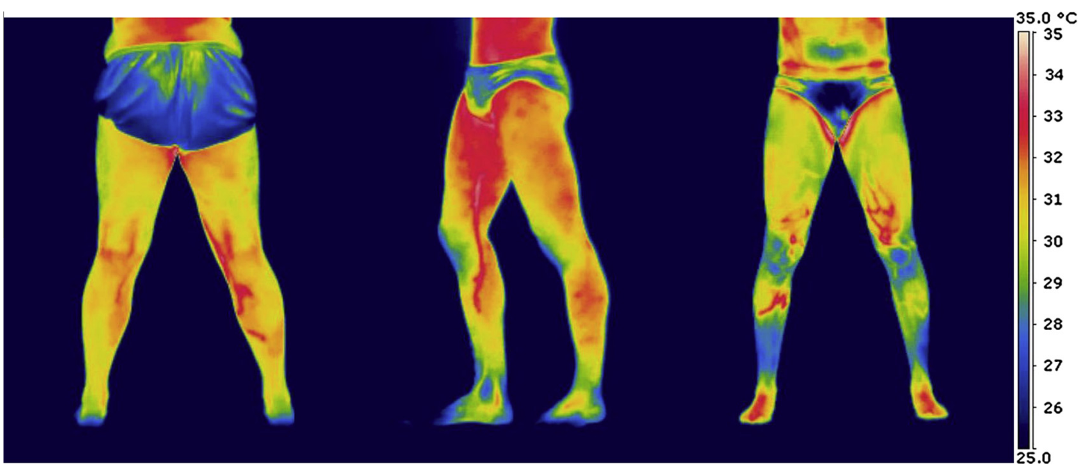

Fig. 6. IRT images showing examples of varicose and superficial veins.

We therefore strongly suggest performing a medical anamnesis prior to a thermographic examination. Information regarding prior injuries, diseases and operations could provide essential information for understanding potential chronic thermal asymmetries that may influence the interpretation of the IRT images.

3.2.1.8. Metabolic rate. Jiang et al. [174] briefly noted that Tsk is the result of the heat balance that is generated by metabolism and heat loss through thermal conduction, forced and natural convection, perspiration and exhalation. Therefore, the influence of metabolism on Tsk is very important but difficult to study [33,35].

The correlation between metabolism and Tsk allowed IRT to be considered a valuable and accurate tool for quantitating heat loss and energy expenditure in humans [91,175,176]. Indeed, one of the most interesting applications of IRT in medicine (e.g., breast cancer) is based on the detection of the higher metabolic activity of carcinomas [2,45,177–180]. However, breast cancer is not the only application where IRT can be used to examine metabolism. Diabetes is a metabolic disease where patients have abnormal temperature patterns in the feet and hands due to the hyperglycaemia that is caused by insulin deficiency [57]. Furthermore, recent studies have stated that IRT is an accurate indicator for diabetes, even better than blood sugar measurements [45,181,182]. Chudecka [168] described hypothermic skin patterns in individuals with eating disorders, due to slower metabolic processes, among many other reasons.

Finally, other studies have measured metabolic activation using IRT. Interesting research is being conducted into the relationship between Brown Adipose Tissue (BAT) and thermogenesis [183]. Some researchers have used IRT in order to measure and locate BAT in the supraclavicular region [91,184], which is related in adults to a lower body weight and fasting glucose level [185]. Additionally, there is a relationship between physical activity and metabolic increases. Physical activity generates a higher body temperature, resulting in heat dissipation through the skin [186,187]. Therefore, IRT evaluation following any type of physical activity may be an effective indicator of metabolic activation. Knab et al. [188] demonstrated increased energy expenditure even 14 h following exercise, and Fernández-Cuevas [189] found through IRT significant warmer Tsk in some body areas 8 h after moderate exercise, including endurance, strength and speed training.

3.2.1.9. Skin blood flow. Skin blood flow has been described as an important factor in heat exchange, along with other factors, including metabolic rate and subcutaneous adipose tissue [35,190]. Consequently, the relation between Tsk and skin blood flow is sufficiently relevant to consider it as one of the primary factors influencing IRT.

Skin blood flow is related to the autonomic nervous system, which controls vasoconstriction and vasodilatation of the capillary vessels to maintain homeostasis [79,191]. Therefore, other factors (i.e., sweating or physical activity) may be directly correlated with skin blood flow.

However, skin blood differs between subjects and may lead to variable Tsk values [79,88,192]. Certain studies have reported opposite reactions in the same conditions, such as the cold test or physical activity [47,193]. These differences may be explained by physical fitness [194], genetic factors [195] or ethnic considerations [196]. A deeper knowledge of the relationship between skin blood flow and Tsk through the use of IRT is required to understand the different influences of skin vascularity and Tsk.

3.2.1.10. Genetics. Human evolution is marked by genetic adaptations to the environment. Thirty-one different climatic zones have been described worldwide, and human beings have physiological and morphological differences in response to their environmental conditions. Lambert and collaborators [196] indicated that phenotypic differences are very clear, but genotypic differences are less easy to discern, despite the discovery of 50 genes affected by heat and 20 by cold.

There are obvious Tsk differences between subjects, due to all the factors that we describe in this review. Nevertheless, we should not forget the theoretical influence of genetics on normal and disordered Tsk and thermal profiles. Although genetic factors are a recurrent topic in research studies, little research has been published describing the genetic influence in Tsk.

However, some authors have noted the importance of investigating the thermal profiles of different population groups or specialisation groups. Bouzas and collaborators [101] published the thermal profile of Brazilian adults and football players, Chudecka et al. [81] described the body surface temperature of obese women, and more recently a general thermal map for young women and men [41]. Other authors focused on the thermal description of some body areas: Hauvik and Mercer [197] described the thermal distribution patterns of the skin surface in the head in bald-headed male subjects; and Gatt et al. [198] published hand and foot Tsk distribution patterns. These are just some recent examples of research studies that have attempted to provide more Tsk data in different population groups. Further research will doubtless drive us logically from general to individual data; genetic research therefore seems to be necessary for understanding differences in Tsk.

3.2.1.11. Emotions. Emotions are another surprising factor that modify Tsk. Although it sounds strange, skin temperature (particularly in the face) varies with mood. Some research studies have been done in this vein, discovering an interesting capacity to identify human feelings.

Initially, some researchers analysed sexual arousal and its influence on skin temperature [199–203]. Some years after, it was described how unpleasant and pleasant states could be identified by IRT [204–206]. Most recently, Legrand and collaborators [207] have showed a negative relation between cheek temperature and affective state – pleasure/displeasure – during exercise. Other authors showed a significant temperature change on nose Tsk under red illumination [208]. Jenkins and collaborators [209] analysed the potential of IRT by measuring cognitive work and affective state changes in humans during user-product interactions. They measured the forehead Tsk and found strong positive correlations between IRT, Electroencephalogram (EEG) reading and Affective Self Report (ASR) scores.

In recent years, the research group of Arcangelo Merla has published a significant number of papers describing the complexity of emotions and how they influence the skin temperature, mainly the facial thermal response. Among many different emotions, they have described mother and child synchrony [210,211]; startle [212]; guilt [213]; fear [214,215]; stress [216–218]; and other emotions [219]. Ioannou and his team [220] have published an impressive review describing the thermal response in different ROI when experiencing different emotions (see Table 2). We can conclude that emotional status can influence thermal assessments. Even if the face is the most critical ROI for thermal signalling of emotions, we suggest taking into account the emotional status of the assessed subjects.

3.2.2. Extrinsic factors

According to the proposed classification, extrinsic factors are considered to be those that affect human skin temperatures for a certain period of time, with the majority of these being external factors. Considering the large list of external factors, they have

Table 2
Skin thermal variations in the considered regions of interest across emotions (based and adapted from Ioannou et al. [220]).

	Emotions									
	Stress	Fear	Embarrassment	Startle	Sexual arousal	Anxiety	Joy	Pain	Guilt	Displeasure (exercise)
Regions										
Nose	↓	↓			↑		↓		↓	
Cheeks				↓						↑
Periorbital				↑	↑	↑				
Supraorbital				↑		↑				
Forehead	↓↑	↓			↑	↑		↓		↑
Maxillary	↓	↓		↓				↓	↓	
Neck–carotid				↑						
Nose	↓									
Tail		↓						↓		
Fingers/palm		↓						↓		
Lips/mouth			↑		↑					

been subdivided according to their primary characteristics: (i) factors that may be intake-related but affect the Tsk; (ii) those that may be applied directly to the skin; (iii) those factors that are related to skin therapies; or (iv) those factors that concern physical activity.

3.2.2.1. Intake factors. In this section, we aim to describe the factors that affect Tsk or emissivity due to the consumption or intake of medications, drinks or other products that could temporarily influence Tsk.

3.2.2.1.1. Drug treatment or medicaments. It is often recommended that the use of medications be avoided prior to a thermographic assessment [3,23,88]. Certain general indications have been described regarding the nature of the drug treatments to avoid, but there is no specific list of medicaments that affect Tsk.

It would appear simple to make a list of all of the medications that influence thermoregulation. However, based on the lack of such a classification in the literature, it appears that the construction of such a list is not as simple a matter as it may appear. Drug treatments can affect Tsk, but to date, the primary use of IRT is to evaluate the therapeutic effects of treatments [221]. Based on the research that has been performed on IRT, we propose a treatment list that consists of five primary groups: analgesics, anti-inflammatories, vasoactives, hormonal medications (contraceptives), prophylactics and anaesthetics.

The first of the effects of medical treatments on Tsk was performed by Ring et al. [37] and Collins et al. [139], who conducted several studies to analyse the effects of different rheumatoid arthritis and gout treatments on IRT. These authors described the manner in which Tsk changed under the effects of non-steroidal anti-inflammatory drugs (NSAID), intra-articular anti-inflammatory steroids and analgesics over several days of treatment. IRT was reported to be a useful tool for the clinical testing of these drugs, using temperature alterations in the affected joints as an objective marker [165].

Some years later, it was described that paracetamol augments Tsk in small joints, whereas a week was required for the same effect with anti-inflammatory treatment [222]. More studies were subsequently published on NSAIDs and thermography [223]. Indeed, Giani et al. [224] demonstrated the usefulness of IRT as a tool to evaluate the use of NSAIDs in sport injuries.

Other treatment groups are related to hormones. The effects of this group of drugs are quite complex, directly affecting metabolism and thus thermoregulation. Uematsu et al. [225] described the flare effect on Tsk following an intradermal injection of histamine.

Contraceptives are the most frequently used hormonal drugs and can significantly alter daily temperatures, shifting the entire curve upward as much as 0.6 °C [73]. Other compounds, such as melatonin, have been demonstrated to affect body temperature [226].

In a chapter on prophylactic treatments, we found an example reported by Henahan [227], who explained how Doctor Jan Frens "*noted that many drugs act on the hypothalamus and other brain centres involved in controlling the body's thermoregulatory system*". It was described how methysergide maleate, which is used as a migraine prophylactic, caused a decrease of in Tsk of 10 °C due to its role as a serotonin antagonist, which regulates body heat loss.

Vasoactive and anti-inflammatory treatments are frequently noted to influence Tsk [23,88,165]. Caramaschi et al. [228] described the use of IRT to describe the effects of an injection of the anti-inflammatory Iloprost on Tsk. Other works that evaluated the effects of drugs that affect the cardiovascular system were mentioned [229–231]. Recently, Bruning and collaborators [232] analysed the effect of antithrombotic therapy with oral aspirin or clopidogrel in Tsk, including 120 min of exercise on a cycle ergometer. The results showed an increased core temperature and Tsk, both during rest and exercise.

However, a detailed investigation should be performed to define the effects of all of these medications on Tsk. Special attention should be given to medications that are frequently used (i.e., paracetamol, aspirin, and contraceptives) and that could affect the interpretation of a thermogram.

3.2.2.1.2. Alcohol. Alcohol intake has been associated with an increase in Tsk due to skin vasodilatation and the consequent augmentation of skin blood flow [233]. Ewing et al. [234] were the first to illustrate this fact using IRT; this study, which described several potentially influential factors, also found that alcohol consumption resulted in "an overall increased temperature and a more diffuse thermal pattern than normal" on the breast.

Some years later, another study used IRT to assess the effects of 25 cc of 40% whisky on hand temperature, showing an increase in Tsk over the 9 min following consumption, an effect that was stronger in the subjects who were not used to drinking alcohol [235] (see Fig. 7). However, the same effects were not observed if the alcohol was consumed with a meal.

Wolf et al. [236] noted in a review that since ancient times, "*it had been believed that alcohol dilates blood vessels, causes flushing, and raises skin temperature*". More recently, however, new investigations have demonstrated that the matter is not as simple as this, and controversy exists due to the obtaining of contradictory results despite the use of similar methods.

Two more recent studies examined the response of the hands, knees and face after drinking alcohol, revealing different effects on Tsk, depending on the body area. The hands had a maximal increase of 1 °C after 15′; meanwhile, the temperatures of the knees increased by only 0.3 °C or even decreased by 0.2 °C [237,238].

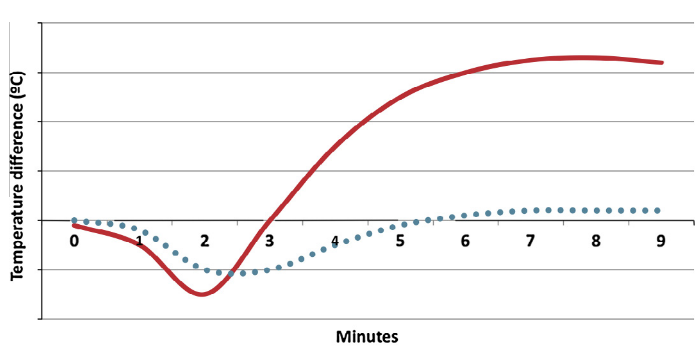

Fig. 7. Effects of alcohol consumption on Tsk between non-drinkers and drinkers (adapted from Mannara et al. [235]).

However, other factors appear to influence the effect of alcohol on Tsk, such as an empty stomach [235], the quantity of the alcohol [239], race [240], the habit of drinking alcohol [235], and even the ambient temperature. It appears that the effects of alcohol only become more apparent between temperatures of 20 °C and 35 °C. In colder or hotter environments, the thermoregulatory system is stronger than the effects of the ethanol [233,241].

As Wolf et al. [236] noted, the primary influence of alcohol on Tsk is vasodilatation and the consequent temperature augmentation. Nevertheless, more research should be performed into the responses of Tsk to alcohol not only on the joints and the face but also over the entire body. Likewise, the duration of this influence should be tested.

3.2.2.1.3. Tobacco. In contrast with the majority of factors that influence Tsk, the effects of smoking have been widely examined. The vasoconstrictive action of nicotine on the skin, and therefore the reduction in temperature, is well known [242]. Nicotine affects both heart rate and blood pressure, but in opposite directions [242,243].

The great interest on the effects of smoking on health encouraged many studies in this field during the 1960s and 1970s. IRT was used to analyse the thermal effects of smoking, primarily on the hands and the feet. The results demonstrated a decrease in temperature of between 0.5 °C and 3.0 °C in the extremities, reaching the lowest point between 15 and 30 min after smoking [56,234,244]. Ewing et al. [234] described a decrease of 3 °C at the breast during smoking, and Gershon-Cohen et al. [56,244] noted that the vasoconstrictive effects remained for 90 min after smoking. The only dissenters regarding this consensus were Usuki et al. [245], who showed an increase in Tsk following consumption of nicotine chewing gum. Recently, Christensen and collaborators [84] reported no significant difference between smokers and non-smokers in their study of changes in facial temperature with IRT. Nevertheless, they suggested that these findings could be due to the low number of smokers in the study and the number of cigarettes smoked per week (only 3 smokers who consumed fewer than 80 cigarettes per week).

It seems clear that smoking affects IRT (i.e., by reducing Tsk); nevertheless, more information regarding the response of other body areas (apart from the hands and the feet) would shed light on the whole-body response to nicotine.

3.2.2.1.4. Stimulants. Caffeine is a commonly used substance. Therefore, knowing the effects of this stimulant, which is present in coffee, tea and soft drinks, is important for the assessment of a thermogram. The reported results highlight the increase in Tsk following the consumption of caffeine [246,247]. Accordingly, Quinlan et al. [248] concluded that the consumption of hot drinks with caffeine activates physiological processes that boost the increase in Tsk. These authors described a thermal peak of 1.7 °C 15 min following the intake of caffeine, with Tsk returning to baseline one hour following consumption [248]. Nevertheless, Koot and Deurenberg [247] noted that the metabolic rate remained elevated for over 3 h due to caffeine consumption, but Tsk was only elevated for 90 min following consumption.

Surprisingly, the only study to use IRT to measure Tsk following the drinking of tea was by Clark et al. [249]; however, the aim of the study was to determine the effectiveness of a cup of hot tea or an ice-cold drink as a cooling strategy, using Tsk as a readout. Amazingly, it was the cup of hot tea. However, it would be advisable to perform further research regarding the effect of caffeine and other stimulants on Tsk using IRT.

3.2.2.1.5. Food intake. Although it is well established that food intake increases body temperature [113] the results regarding its impact on Tsk are inconclusive [3].

Certain studies have analysed the effects of food intake on Tsk using IRT, finding no changes [235,250,251]. Others have observed that the timing of food intake did not alter the circadian rhythm [19,104].

In contrast, other investigations have reported opposite conclusions. First, Kelly [160] described in his review how the timing of food intake influences metabolism, taking, for example, the case of Ramadan, during which Muslims abstain from eating and drinking between sunrise and sunset for 30 days. Food intake is related to an increase in oxygen consumption and energy expenditure [252], which is referred to as Diet-Induced Thermogenesis (DIT). It is believed that DIT is caused by the triggering of intestinal, liver and Brown Adipose Tissue (BAT) activity [253]. However, the investigations that were performed along these lines were not able to determine the role that the liver or BAT played, even if Tsk was observed to rise using IRT [175,194,254]. Certain authors described differences between the increase in metabolic rate and Tsk in the postprandial period, reporting a rapid effect on energy consumption immediately after eating [251,252]. Nonetheless, Tsk reacts later, peaking between 60 and 90 min after eating, followed by an initial and smooth decrease [175,252,254] (see Fig. 8). Further studies using IRT could shed light regarding the primary body areas that are influenced by eating and to determine whether the quantity or quality of the food eaten has any effects on Tsk.

3.2.2.1.6. Hydration. It could be suggested that normal hydration does not affect Tsk, because drinking does not entail digestion and therefore is not an energy-releasing process. However, it has been reported that sparkling water consumption in humans caused a drop in Tsk in the hands, knees and face of up to −0.89 °C [238] (see Fig. 9).

The aim of this study was to investigate the influence of alcohol on Tsk; it was therefore surprising to discover a reduction in Tsk in the control group. This effect was perhaps due to the concentration of CO_2 in the sparkling water. This was the only study to find a relationship between hydration level and Tsk; therefore, more studies are required if we are to understand this potential influence.

3.2.2.2. Application factors. The second group of extrinsic factors refers to those that are applied directly on the skin and which affect the skin's emissivity or blood flow. Such factors include cosmetics, ointments, topical products and radiation.

3.2.2.2.1. Ointments and cosmetics. Scientific studies of IRT frequently provide recommendations regarding the procedures that should be followed to achieve a neutral IRT evaluation. Thus far, ointments, creams, makeup, deodorants, antiperspirants and oils are often cited as items to be avoided by the subject prior to the assessment [2,3,6,9,23,28,29,45,47,101,128,227,255–260]. However, it is difficult to find specific studies that have analysed the effect of the topical factors that Vainer [261] referred to as "unnatural factors", which are often used in daily life.

We suggest differentiating these factors into the following categories: cosmetics (makeup, deodorant, antiperspirants, talc, etc.), ointments (creams, oil, skin lotions, etc.) and medicated ointments (analgesic, vasodilators, cold gel, spray, etc.).

An early study of the influence of ointments and cosmetics analysed the manner in which different products, such as sun cream, talcum, Vaseline or oil, can influence skin emissivity [262]. Unfortunately, this author did not specifically describe the effects in terms of the extent of the increase or decrease. Nevertheless, other authors have subsequently described a direct influence of this type of topical product on Tsk [227,261,263–265]. These products primarily mask the true Tsk and give the skin a different emissivity. Therefore, the recorded Tsk is decreased [266].

Henahan [227] reported differences between non-medicated and medicated ointments. Certain medicated ointments, such as those with nicotinic acid or oestrogenic hormones, function as vasodilators and can cause local hot spots that can persist for

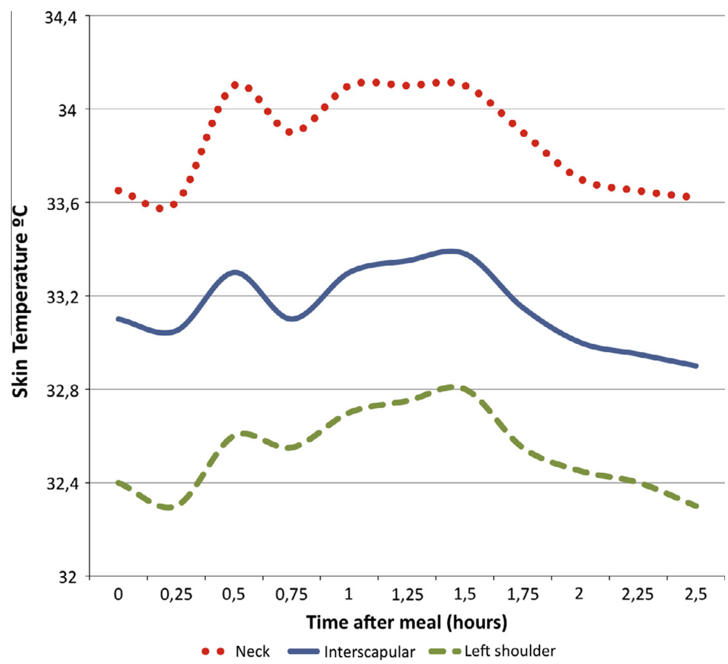

Fig. 8. Effects of food intake on Tsk (adapted from Dauncey et al. [254]).

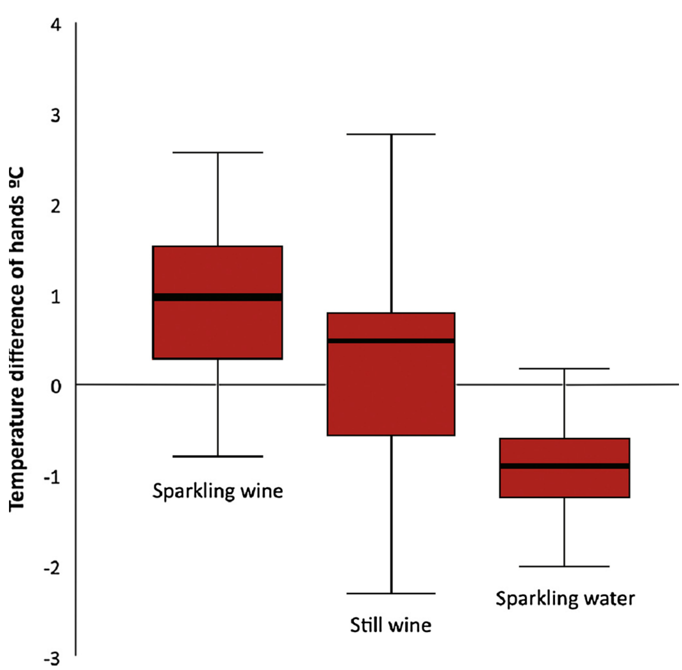

Fig. 9. Effects of sparkling water intake on Tsk of the hands (adapted from Ammer [238]).

24 h [264,265]. Other medicated ointments have been reported to have the opposite effect, such as Deep Freeze Cold Gel, which was used by Ring et al. to conclusively demonstrate a decrease in Tsk due to, among other reasons, the evaporation of alcohol [1]. Another recent publication described a skin cooling effect of topical Voltaren® [267].

A study reported Tsk measured using IRT following the application of several innocuous products, such as ethylic alcohol, Vaseline, penicillin cream, moisturising creams, baby oil, talc, Melox, ultrasound imaging gel, sun tanning products and sunscreen. The aim of the investigation was to enhance the contrast between Tsk and the subcutaneous veins, and sunscreens were determined to be the best product for decreasing Tsk in order to improve visualisation of veins [266].

Recently, Bernard and his team [268] have published an interesting work attempting to determine whether the skin emissivity can be neglected or not in situations of topical application of substances such as ultrasound gel, ointment and disinfection. They showed cooler thermal results on hands with those ointments, due to a different emissivity.

Moreover, hypoallergenic massage cream has been used by several authors to prevent creams from being a confounding factor [269]. Therefore, the effect will be different depending on the content of the topical product used. More research is required to establish how long the effect persists.

3.2.2.2.2. Water. Certain authors recommend that showers be avoided for one or two hours prior to a thermographic evaluation [2,258,270]. Again, there is a lack of references explaining the reasons to avoid showers. Clearly, the application of water on the skin depends on the manner in which it is applied (e.g., ice pack, a sauna, cryotherapy, or hot or cold showers). Nonetheless, the majority of these examples will be described in Section 3.2.2.3.

A recent study has examined IRT results between two hands, applying in one of them water at body temperature (35 °C). They found that water entails lower Tsk results, but not due to the water temperature, but the emissivity [268]. The hydration of the skin through a shower or a bath is expected to influence Tsk; thus, we suggest that subjects should avoid showers or baths prior to the thermographic evaluation.

3.2.2.2.3. Sunlight. Another factor commonly mentioned factor to be avoided is heat radiation. A large number of studies suggest performing the infrared evaluation in a standardised and air-conditioned room without radiation sources, such as direct sunlight [2,45,58,88,139,162,259,271]. The influence of sunlight is more frequent and problematic for other IRT applications, such as veterinary thermography, due to a greater exposure of the subjects to sunlight and the difficulties in avoiding exposure [272].

The most interesting publication that studied this factor was performed by Clark and his collaborators in 1977 [249]. These authors performed an experiment to determine the effect of sunbathing for 20 min at a temperature of 31 °C. Using IRT, these authors observed an augmentation of 5 °C on the side exposed to the sun, with an accompanying reduction in the whole body Tsk range from the normal 8–10 °C to 4–5 °C [249].

3.2.2.3. Therapies. These influences are therapies that are applied on the skin and therefore affect the skin's radiation and temperature. We will mention the references for the most current therapies and methods from physiotherapy, although other lesser-known therapies may influence Tsk as well.

Electrotherapy is a medical treatment that uses electrical energy. In physiotherapy, the wave frequency, wavelength and intensity of the stimulus can be modified to achieve different objectives, e.g., pain management, improved muscle performance, tissue repair and increased functional activity [273]. Ring and Ammer [3] cited different authors who described the effects of electrotherapy on Tsk. Unfortunately, these references are not easily obtained. Nevertheless, another interesting study mentioned the different effects of electrical and manual acupuncture, demonstrating a localised short-term cooling effect with an increase in sympathetic activity when using the electrical modality [274]. We have observed similar effects (unpublished observation) (see Fig. 10).

Ultrasound is used in physiotherapy to transmit ultrasonic waves directly to the skin. These waves are absorbed primarily by connective tissue, i.e., ligaments, tendons and fascia [275]. Ultrasound has two principal effects: thermal, due to the absorption of ultrasonic waves, and non-thermal, based on the cavitational effects due to vibrations [276]. Watson [275] observed an increase of 3 °C using IRT following a 5-min application of ultrasound on the hand. In another study, a similar procedure was followed to verify the thermal recovery of muscle following warming by 5 °C with ultrasound therapy [277]. A swift return to baseline was reported, requiring only 18 min for recovery to the initial temperature.

Heat treatment is a common therapy for injuries and diseases. Clearly, the effect of this treatment leads to different degrees of increase in Tsk depending on the manner in which the heat is applied (e.g., hot packs, diathermy or infrared pads) and the duration of the treatment [278,279]. The application of heat has been widely used and observed [280]; and recently described through an IRT study where Visible and near infrared irradiation (VIS–NIR) was applied, increasing the Tsk more than 3 °C but returning the initial thermal values after 30 min in young subjects [100].

Cryotherapy is, in contrast, one of the most investigated topics in the IRT field [80,100,193,259,281–297]. Cryotherapy is defined as the cooling of an area with a medical aim. These goals can be to reduce oedema, to decrease tissue metabolism or to provide analgesia [298]. There are several cryotherapy modalities, including whole body cryotherapy (WBC), cold-water immersion (CWI), ice and cold packs. Each of these modalities has different effects on Tsk [193,299].

In an interesting recent review, Costello and collaborators [193] listed the most relevant works that used IRT to analyse the effects of cryotherapy. Recent cryotherapy guidelines recommend reductions of Tsk between 5 and 15 °C, with 12 °C being the Tsk limit set by experts due to the risk of injuries [300]. For all of the references cited, nearly all modalities reached a minimum reduction of 5 °C in Tsk, and a subset of these obtained decreases of over 15 °C [282,290,292,301–303]. A single case of cooling by WBC decreased Tsk by less than 5 °C [283].

Greater thermal reductions with cryotherapy are achieved in the limbs, joints, hands and feet [282,290,292,301–304]. Meanwhile, core areas (i.e., pectoral or back regions) do not undergo decreases of more than 7 °C [285–288]. With respect to the duration of thermal effects, the majority of studies did not report a return to the baseline levels of temperature even 120 min following the treatment, with Tsk normally remaining several degrees below the baseline measurement [287,288,292,302,303]. Surprisingly, we identified certain studies in which baseline Tsk was reached some minutes following the

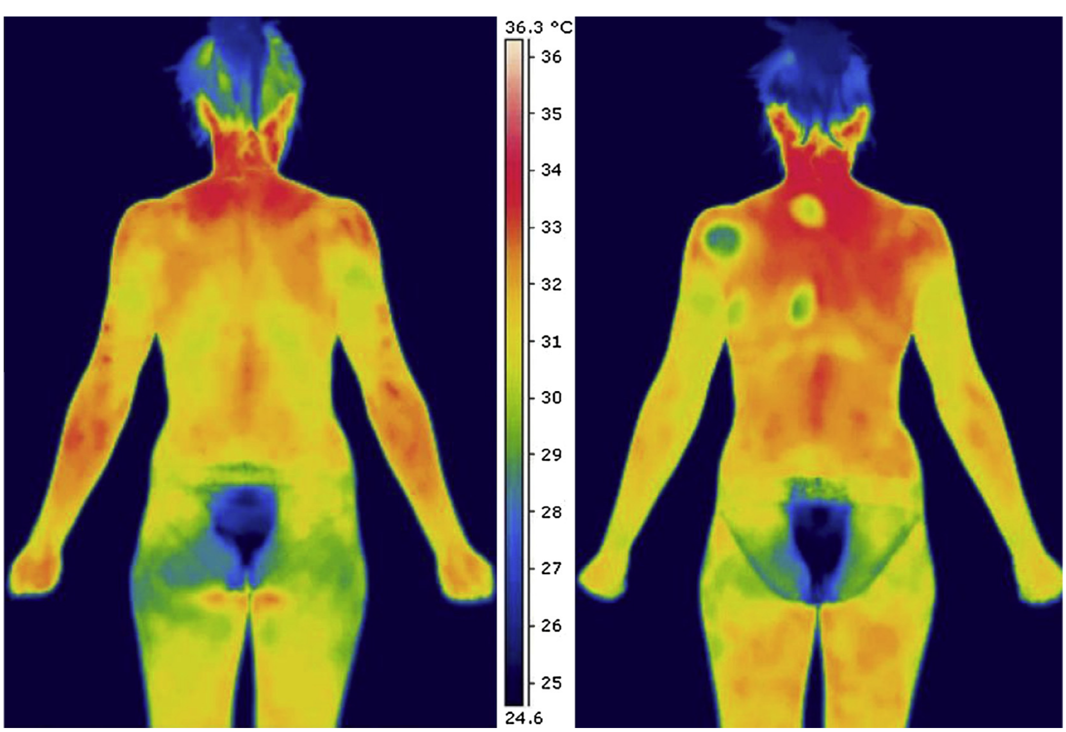

Fig. 10. Example of the effects of electrotherapy before (left) and after 10′ of treatment (right).

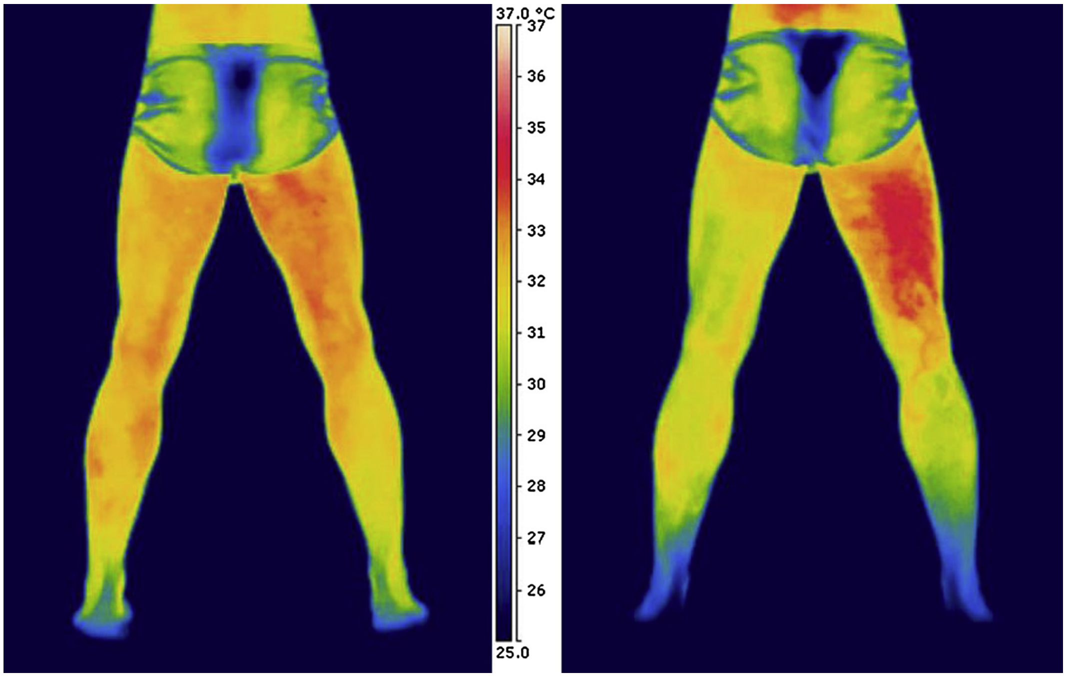

Fig. 11. Example of the effects of effleurage massage (sport technique) before and after 10′ of treatment on the posterior right thigh.

cold test [99,282], with hyperthermia of 1 °C or even higher being reported. Both studies analysed the extremities, such as the hands [99] and the forearm [282]. Some research has been done to analyse the effects of cryotherapy in women depending on age [296]. One study used a covering of ice for only 30 s [282] and employed a brief (2 min) cold water immersion [99]. However, we highlight the exceptionality of these investigations and emphasise that the general tendency is for the Tsk to remain lower for 2 h following cryotherapy.

Massage is traditionally used to obtain therapeutic or medical objectives. There are many massage techniques; however, the majority of these techniques require direct contact with the skin. The thermal effects of this therapy have been examined using IRT, and an increase in Tsk has been reported [269,305–311]. Effleurage massage (a sports technique) achieved the greatest augmentation of Tsk (approximately 1.8 °C with 10′ and 2.8 °C with 30′ of massage) [307] (see Fig. 11). Generally, Tsk increases approximately 0.5 °C with a 20-min massage [269,305,306,311]. Sefton et al. [269] analysed the thermal effect of a 20-min massage of different body areas, describing a general tendency of Tsk to increase as much as approximately 0.7 °C (even in non-massaged body areas), peaking 35′ after the massage session and returning to baseline after 60′. Differences were observed between the regions, with the hands exhibiting hypothermia and the back of the neck remaining 0.4 °C warmer after 60 min. Moreover, it was observed that mobilisation techniques cause non-significant Tsk increases [308] or even slight decreases [51,309]. Holey et al. [309] performed an investigation of connective tissue massage (CTM) using two techniques, fascial and flashige massage. The authors reported 0.8 °C increments with the fascial technique and 0.1 °C decreases with the flashige technique; these trends were maintained after 60 min. Scraping therapy is another technique which causes an increase in Tsk. Xu et al. [312] reported an increase of 1.7 °C immediately after the therapy, and areas that were 0.7 °C warmer persisted for 90 min after the use of the technique. In summary, massage therapy commonly results in increased Tsk with a relatively rapid return to the thermal baseline; nevertheless, more investigations could provide further knowledge about the thermal response and influence the grade of the different techniques.

Other therapies are related to certain previously described modalities, such as **hydrotherapy**, which is based on the use of water for pain relief and treatment. Essentially, hydrotherapy uses cold water, hot water, or both (a technique that is referred to as contrast hydrotherapy). We previously mentioned the effects of cold-water immersion (CWI) [99,302,304]. However, less has been written with respect to hot water [313]. Ring et al. [314] described an increase of 5 °C in Tsk on the ankles following hot water immersion, and a 2.4 °C increase was observed for the knees; more than 2 h were required for the Tsk to reach baseline levels. However, this previous study used thermistors rather than IRT. It is therefore necessary to further investigate the thermal response of the skin following hot water exposure, as well as the effects of other daily previously mentioned activities, such as showering or bathing.

Acupuncture has been studied in many investigations that used IRT to search for thermal differences in meridians and acupuncture points [274,315–326]. We are aware of the existence of more studies, but the majority of these are inaccessible from western databases, as they are Asian publications. Nonetheless, studies such as one conducted by Lo [327] described the thermal effects of acupuncture therapies, with Tsk decreases of up to 1.48 °C and augmentations of up to 0.69 °C. Ipólito and Ferreira [326] reported a significant reduction in leg Tsk by approximately 1.1 °C in all volunteers after 15 min of therapy. In the majority of these cases, the acupuncture treatment was performed in body areas far from the painful region that exhibited increased temperatures. IRT could certainly aid in the better understanding of the thermal effects of this traditional Chinese technique.

As we have seen, the influence of the above therapies on Tsk is clear; therefore, these factors should be avoided or reported prior to a thermographic assessment [2,23,45,258]. Ring and Ammer [3] described thermal effects between 4 and 6 h following therapy. Nevertheless, this long-term effect has not been described in any study that was present in the database used in this review.

3.2.2.4. Physical activity. In this group, we will include factors that are related to physical activity and exercise, which are likely to be some of the primary sources of homeostatic disturbance in the human body [64,65,162,328,329]. We have also included other factors, such as sweating, fitness level, limb or hand dominance or specific thermal distributions that are due to a sport specialisation.

3.2.2.4.1. Recent activity. Muscle activity is one of the principal heat sources of the human body [64,162,328,330]. Therefore, exercise is considered to be one of the strongest influences on Tsk. Consequently, many authors recommend avoiding exercise prior to an IRT evaluation [3,23,28,331]. However, it is difficult to find studies that analysed the thermal effects of physical activity on Tsk.

Physical activity and exercise appear to be one of the most potentially promising IRT applications. Indeed, technological advances in infrared cameras have allowed for a resurgence of investigation in this sector, enhancing new and old applications, such as the following:

- The quantification of training workload [168,332–334].
- The detection of anatomical and biomechanical imbalances [335,336].
- The evaluation of fitness and performance conditions [39,47,137,337–340].
- The detection of high temperature risk in pregnant women [341].
- The detection of delayed onset muscle soreness (DOMS) [342].
- The prevention and monitoring of injuries [34,48,68,144,294,343–350].
- The evaluation of efficiency level by some disciplines [351].
- The detection of the lactate threshold [36,352].
- The monitoring of the respiration rate [353].
- Clothing design and thermal comfort [83,354–360].

Studies of the thermal response following exercise have reported both increases and decreases in Tsk immediately following exercise. One of the primary reasons for these contradictory results lies in the type and the duration of exercise. Normally, increasing Tsk is related to constant and prolonged aerobic tasks [68,361–363], whereas studies that report decreasing Tsk primarily utilised brief intense or maximal exercises [36,47,65,66,68,137,307,351,364–366].

Fernández-Cuevas [189] reported the Tsk response after three different training methods: endurance, strength and speed training. The results were different depending on the ROI analysed, but the most impressive outcomes were those indicating significantly warmer Tsk in some areas of the body 8 h after exercise. Therefore, IRT evaluations after exercise should take into account the last physical activity.

Besides the type, duration of exercise and ROI analysed, other important factor is the intensity. Malkinson [43] affirmed that a bigger intensity is related with a major increase in Tsk. Other works with bigger samples have showed the opposite: there is indirect relationship between exercise intensity and Tsk [66,367].

We entitled this section "recent activity" rather than "physical activity" because other types of exercise can influence Tsk, even if they are not strictly related to sports. Thus, sexual activity should be considered to be an influencing factor, not only due to the same reasons as exercise but also given that – as some authors have documented – sexual arousal, masturbation or sexual intercourse affect Tsk in the genital areas [199,203], as well as in other ROIs, such as the abdomen or the breast [200,202].

3.2.2.4.2. Sweating. As mentioned, in the sections in hydration and hydrotherapy, water can influence skin emissivity and can therefore alter the results of IRT in humans. Sweating represents a thermoregulatory response to heat production by dissipating excess heat by evaporation [368,369]. The majority of authors have described the cooling effect of sweating on Tsk using IRT [35,36,39,337,357,370–372], with the exception of Torii et al. [63], who reported that this cooling effect is not due to sweating but to vasoconstriction. However, few authors have focused on the potential influence of sweating as a factor that influences IRT results. Ammer [373] highlighted this influence on skin emissivity, hypothesising that sweat acts as a filter for infrared radiation and that sweat may have a prolonged cooling evaporation effect.

In conclusion, sweating represents a factor that affects Tsk (primarily in specific situations, such as exercise). Therefore, sweating could influence the results of IRT in humans.

3.2.2.4.3. Fitness level. As described in the section on medical history, the ideal "homeothermy" of each subject changes throughout life. Individual thermal pattern changes are unique for each subject at any given moment of their lives. Individual fitness level can also influence the thermal pattern. Cena and Clark [374] were the first to underline the difference in thermal emissions between trained and undertrained subjects. More recent studies have demonstrated differences in thermoregulation depending on the fitness and expertise level of the subject [40,307,339,375,376]. Untrained subjects exhibit a poor cooling capacity during exercise, and their recovery is less rapid [40,339,365,377]. Moreover, Akimov and his collaborators [36,194,338] have recently demonstrated a relationship between the human thermal portrait and aerobic working capacity and blood lactate levels, both of which are indicators of the fitness level. Therefore, some authors have already highlighted the potential of IRT to be used as an indicator of athletic performance and fitness level [168,339]. Further investigation is necessary to establish whether differences exist in the thermal pattern at rest between trained and untrained subjects.

3.2.2.4.4. Dominance. Side-to-side comparisons of bilateral body areas are commonly used to detect abnormal Tsk patterns [53,378]. Several authors have described side-to-side Tsk asymmetries in healthy subjects [53,55,88,89,101,108,158] and in those with pathologies [107,150,379–381]. In the first thermographic studies, the normal side-to-side difference was set at 1.0 °C [55,119]; however, as IRT has become more accurate, the normal side-to-side asymmetry ranges have narrowed (see Table 3).

In the most recent studies, Vardasca et al. [383] determined the overall temperature symmetry difference to be 0.25 °C ± 0.2 °C. Likewise, Bouzas Marins and collaborators [101] showed average Tsk differences in young soccer players to be less than 0.2 °C and indicated that the Tsk differences happened in the dominant leg, a result that had been previously described by Gómez Carmona [34]. Additionally, another recent study described the application of IRT to detect Limb Length Discrepancy (LLD), studying thermal

Table 3
Skin temperature asymmetries results from different studies of IRT.

Year	Author	*N*	Subjects	ROI	Asymmetries
1963	Barnes [119]	100	Patients	Breast	>1 °C
1984	Feldman and Nickoloff [55]	100	Healthy	Normative data	>1 °C
1985	Uematsu [379]	32	Healthy	Knee	0.24 °C
1988	Uematsu et al. [53]	90	Healthy	Forehead, leg and foot	0.18 (±0.18) to 0.38 °C (±0.31)
1990	Ring [108]	150	Healthy	Legs	0.17 (±0.16) to 0.28 °C (±0.22)
1992	BenEliyahu [343]	70	Patients and healthy	Knee	0.5 °C
1999	Zhu and Xin [158]	233	Healthy	Different ROIs	0.6–1.8 °C
2001	Niu et al. [89]	57	Healthy	Different ROIs	0.2–0.5 °C
2009	Hildebrandt and Raschner [382]	10	Healthy	Knee	0.1 °C
2012	Vardasca et al. [383]	39	Healthy	Total body	0.4 ± 0.3 °C
2014	Bouzas Marins et al. [101]	100	Healthy athletes	Legs	<0.2 °C

asymmetries in contralateral body parts following the use of artificial imbalances (by placing a 20-mm foot support under the dominant foot).

Nevertheless, other authors have suggested that side-to-side differences in healthy subjects are nearly zero [384]. They affirmed that limb dominance does not affect temperature asymmetry in the patellar tendon or the wrist extensor tendon, with the observed side-to-side differences being lower than 0.02 °C.

However, due to the very large differences in the reported Tsks of different body areas, we suggest that further investigations be performed to establish maximal normal asymmetries in healthy subjects.

3.2.2.4.5. Specialisation. Similar to the above results, sport specialisation could affect normal thermal patterns in healthy subjects [344]. Athletes who participate in different sports have been assessed using IRT. These studies have been performed on athletes that participate in running [47,68,361,366], swimming [68,385–388], tennis [389], football [34,68,101,344], handball [39,372,390], cycling [137,351,363,367,391], rowing [344], basketball [392,393], judo [394], strength training [334,395], water polo [396], wrestling and weight lifting [344], volleyball [337], American football [397], rugby [144,289], triathlon [68], gymnastics [345,398], and skiing [68], as well as less conventional athletic disciplines, such as Taijiquan [376].

One application of IRT in sports is for the detection of side-to-side asymmetries in Tsk, which can be used to identify abnormalities, prevent injuries [34,68,101] or monitor the healing of a sports injury [346]. Knowing the specific thermal patterns of each athlete and the pattern that is generally exhibited by participants in a particular sport aids in the proper evaluation of such asymmetries. These studies are important given that, as certain publications have shown, specialisation can lead to sport-specific but "normal" asymmetries, such as the forearm in tennis players [389], the tibialis anterior in football players [34], the arm in volleyball and handball players [39,337,372], and the grasping forearm of a judoka [394].

Asymmetries in Tsk are a frequent result of sport specialisation. As Tauchmannova and collaborators [344] highlighted in a very interesting study analysing 70 top sportsmen from five different sport specialities, including weight lifting, wrestling, rowing, football and handball, further investigations are highly recommended in order to create a thermal pattern for each sport, as well as for any type of work or physical activity, and even for each individual, to aid in the appropriate interpretation of the acquired thermograms.

3.3. Technical factors

The final group of potentially confounding factors is related to equipment. As mentioned in the introduction, the revival of IRT is due in great part to technological improvements in the previous decades. Nevertheless, higher resolution, novel features (such as 3D IRT) and superior accuracy do not imply that technical factors have less of an influence on the proper collection of human IRT data.

3.3.1. Validity

Accurate and consistent seem to be similar adjectives, but they are not. Accuracy is directly related to validity, and validity refers to whether a measurement is well founded and corresponds accurately to the real world. Reliability is related to consistency, and it will be discussed in the next section.

As previously mentioned, validity refers to whether a measurement is well founded and corresponds accurately to the real world. In the case of IRT, validity would be the ability to estimate temperatures of an object's surface from its infrared radiation as recorded using a thermal camera. Burnham et al. [399] demonstrated that skin infrared thermometers have good validity ($r = 0.92$), but only Sherman et al. [163] published a study of the validation of "videothermography", i.e., IRT.

Several technical improvements have been made in IRT in the previous decades, including the number of frames per second, resolution, and the weight of the equipment.

Accuracy is directly related to the validity of IRT because it refers to how close the thermal readings of an IRT camera are to the true temperature. Even if the accuracy has improved, IRT-based measurements can be more than 1 °C (or 1%) different from the actual temperature (even in the best cameras). This is not a large error in the evaluation of a building or in an industrial setting. However, considering how important precision is in measuring human temperatures (more than 0.25 °C of side-to-side asymmetry is considered to be abnormal), poor accuracy could represent one of the weakest points of IRT.

The validity of IRT as a diagnostic tool has been conclusively demonstrated in the context of several pathologies and injuries, including reflex sympathetic dystrophy [150], stress fractures [133], psoriatic arthritis [136], complex regional pain syndrome [381,400,401], some knee pathologies [402], pneumothorax [403], localised scleroderma [404], dermatological pathologies [405] and diabetes [182]. It has been also demonstrated for psychophysiological applications [220]. Therefore, Faust et al. [406] affirmed that the future of medicine is related to computer-aided diagnosis systems, and IRT has been showed as a valid diagnostic tool, better than its reputation. However, studies of its validity have been performed only for specific applications [42,58].

3.3.2. Reliability

Reliability refers to the degree to which the measurement gives the same result in repeated measurements. Likewise, repeatability and reproducibility are sub-terms of reliability, all of them related to consistency. In quantitative research, reliability studies aim to prove the consistency of analytic methods or instruments, for example, in determining if a manual analytic methodology gives the same results independently of the observer who takes the IRT image. Reproducibility is more related to the consistency of results over time, obtained with a different, but similar procedure, i.e., investigating if Tsk measurements are consistent in real time as well as at 5 s, 24 h, or two months (see Fig. 12). Repeatability is related to the consistency of findings obtained after the same procedure was repeated [407].

However, those concepts are often mixed in the literature, and reliability is the most commonly used concept for describing the consistency of Tsk measurements. There are different statistical techniques for to investigating reliability and reproducibility. The intra-class correlation coefficient (ICC) is the most commonly used coefficient to describe consistency (intra and inter-examiner). In addition to this two-way mixed model, the coefficient of variation (CV) represents another useful coefficient to show the dispersion of data, but is used less often in the current literature. Lastly, Bland–Altman plots are an illustrative way to visualise the dispersion of data with agreement limits.

IRT reliability has been examined in several studies, both with patients [140,259,382,400,408–410] and healthy subjects [9,164,411]. The majority of these studies achieved ICCs that ranged between 0.4 and 0.9 (see Table 4). Other studies has also analysed IRT reliability during exercise, indicating a poor reliability compared to other technologies as thermistors [362,412,413]. Concerning studies without exercise, Fernández-Cuevas [414] had one of the best results (ICC = 0.989), most likely due to the use of computer-aided interpretation. Automation of ROI determination improves the reliability of IRT and allows for a more rapid and more efficient IRT analysis of human thermograms.

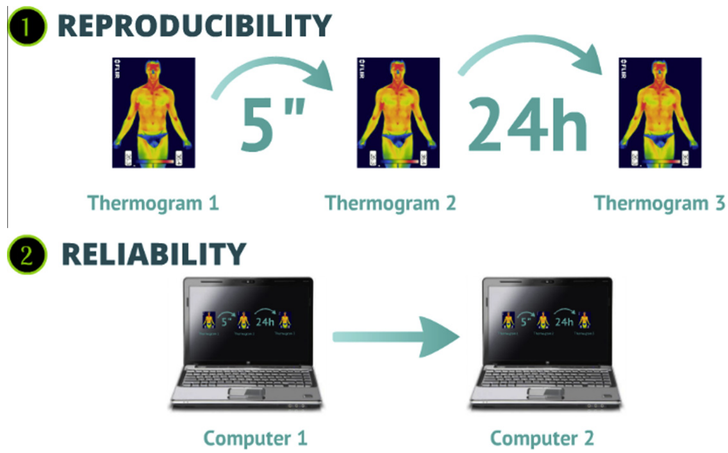

Fig. 12. Representation of the difference between reliable and reproducible study design.

Table 4
Reliability results (ICC) of several published articles on IRT validity.

Year	Author	*N*	Sample	Pathology	Technique	ROI	ICC
1991	Plaugher et al. [415]	19	Healthy		IRT	Paraspinal	0.5–0.8
1999	Oerlemans et al. [380]	13	Patients	Reflex Sympathetic Dystrophy (RSD)	IRT thermometer	Hands	0.94
2003	Ammer [416]	1	Healthy		IRT	Arm	0.48–0.87
2004	Owens et al. [58]	30	Healthy		IRT scanner	Paraspinal	0.92–0.97
2004	Huygen et al. [401]	31	Patients and healthy	Complex Regional Pain Syndrome type I (CRPS1)	IRT	Hands	0.78–0.86
2004	Varju et al. [138]	91	Patients	Hand Osteoarthritis	IRT	Hands	0.899
2006	Burnham et al. [399]	17	Healthy		IRT thermometer	Different ROIs	0.97
2006	Selfe et al. [259]	9	Patients	Anterior Knee Pain	IRT	Knee	0.82–0.97
2007	Hart et al. [417]	30	Healthy		IRT scanner	Spine	>0.75
2008	Spalding et al. [140]	5	Patients	Wrist Arthritis	IRT	Wrist	0.99
2008	Zaproudina et al. [9]	16	Healthy		IRT	Different ROIs	0.47
2009	Gold et al. [418]	45	Patients and healthy	Upper Extremity Musculoskeletal Disorder (UEMSD)	IRT	Hands	0.46–0.85
2009	Hildebrandt and Raschner [382]	15	Patients and healthy	Knee injuries	IRT	Knee	0.75–0.85
2010	Denoble et al. [408]	30	Patients and healthy	Knee Osteoarthritis	IRT	Knee	0.5–0.72
2011	McCoy et al. [419]	100	Healthy		IRT scanner	Spine	0.95–0.97
2011	Pauling et al. [411]	15	Healthy		IRT	Hands	0.83–0.96
2012	Fernández-Cuevas et al. [414]	22	Healthy overweight		IRT	Different ROIs	0.989
2012	Costa et al. [409]	62	Patients and healthy	Temporomandibular Disorder (TMD)	IRT	Face and neck	0.85–0.99
2012	Fernández-Cuevas [189]	32	Healthy		IRT	Different ROIs	0.68–0.99
2013	Choi et al. [400]	28	Patients	Complex Regional Pain Syndrome (CRPS)	IRT	Limbs	0.865
2013	Rodrigues-Bigaton et al. [270]	30	Patients and healthy	Temporomandibular Disorder (TMD)	IRT	Face	0.84–0.87
2014	Rossignoli et al. [410]	24	Patients	Wheelchair users (WCUs)	IRT	Different ROIs	0.39–0.79

Although the results of the Termotracker® are not perfect (ICC = 0.999); it indicates that software solutions are faster and more accurate for the analysis of IRT images than manual methods [414]. Therefore, further investigations aimed at improving interpretive software are clearly needed.

In terms of the reproducibility of results, some studies [9,382,414] noted that, when tracking a single ROI over time (e.g., monitoring an injury), muscular and central ROI measurements are more reproducible (e.g., Abdominal, Back, Thigh, Lumbar, Dorsal), and the worst ICCs were from joint ROIs (e.g., Knee, Ankle, Elbow). However, when examining asymmetries or bilateral values (ΔT), which are actually very useful tools for detecting pathologies [89] or injury risk [34], the most reliable ΔT values are for the joints and the central ROI (i.e., the Pectoral and Shoulder ROIs).

3.3.3. Protocol

An important way to improve IRT in humans and to minimise the potential influence of technical factors is to use a standardised protocol [420]. Because IRT is applied in the medical sector, several organisations have generated and published their own protocols and quality assurance guidelines [23,258,421].

Of the large number of academies, associations and societies, the European Association of Thermology (EAT) has been one of the most active in previous years in publishing IRT-related studies. Importantly, the EAT has contributed studies by the group from the University of Glamorgan, which has worked to better understand the technical factors that affect IRT measurements and to create a strict protocol for reducing errors and increasing the accuracy and the precision of temperature measurements [3,18,165,416,420–424]. Their work is summarised in the

Glamorgan Protocol [424]. Also, this group gathered the primary published outcomes regarding the technical factors that affect IRT data collection for other protocols.

3.3.3.1. Distance. Certain authors have mentioned the importance of the distance between the camera and the subject [3,22,24,425]; however, the majority of studies use different distances that depend on the measured area and the optical characteristics of the camera.

The atmosphere transmits its own radiation between the body and the camera. Furthermore, the atmosphere allows much of the radiation from the body to pass through but also absorbs a small portion of the outgoing radiation. Therefore, there is little radiation loss from the body through the intervening atmosphere. Radiation that is emitted by the body, as well as that reflected from the environment, are equally affected by the atmosphere [424]. This variable is corrected by entering the distance on the IRT camera (Fig. 13).

Ammer [426] performed a study to describe the influence of the number of pixels (a measure that is related to the size of the measured area and the distance between the camera and the subject) on the temperature that is registered by a thermal imager. This author concluded that the results differed when the size of the measured area differed by 100% or more, with a strong influence of the ambient temperature.

Ivanitsky et al. [22] analysed infrared cameras that measured 3–5 μm and 8–12 μm wavelength ranges at different distances, concluding that 3–5 μm wavelength cameras remain stable over a distance of 1 metre, whereas 8–12 μm cameras returned consistent results at distances of up to 2.5 m. For cases outside of laboratory research, Chiang's group [24] has studied the optimal distance between the subject and imager in order to identify patients who may have fever.

Lastly, two studies by Tkacova et al. [425,427] analysed the importance of camera-subject distance, demonstrating a small difference of 0.2 °C between measurements that were performed at 0.2 m and 2.5 m. It has been suggested that distance is less important than the ambient temperature for obtaining valid measurements [420,425,427]; however, we recommend using a short distance if the target of the data collection is a fixed body area, in order to increase the number of pixels and hence the thermal information from the area.

3.3.3.2. Background. The use of a uniform and matte background is mentioned in certain studies [48,60] to aid in the avoidance of reflections from other sources of light or even radiation from the subject in the background. To our knowledge, no study has been performed regarding the influence of different background types and materials on human IRT recordings.

3.3.3.3. Camera position. Another factor that may influence IRT images is the position of the camera. More than the height from which the camera is used, the primary factor that is likely to affect IRT recording is the angle that is subtended by the field of view of the camera on the surface to be measured. Watmough and his collaborators [428] determined that the errors in surface temperature measurements are small for viewing angles up to 90°. These results were in accordance with those of Clark et al. [429], who reported the importance of viewing angles on the record of IRT images. Some years later, Ammer [416] described that small losses begin to occur for angles of greater than 30° and that the loss of information becomes critical for angles of 60° and may lead to inaccurate temperature readings. Chen et al. [430] explained in their study that the loss of information due to the angle of view is based on Lambert's law and could be mathematically corrected. Tkacova et al. [425] performed an experiment to describe the importance of distance and angle, concluding that minimal alterations occur by modifying the angle (see Fig. 13). In addition to those studies with humans, Westermann and collaborators [431] carried out a study with horses to analyse the effects of infrared camera angle and distance. They conclude that thermographically determined temperatures were unaffected by 20-degree changes in the camera angle or a 0.5-m increase in camera distance from the forelimb.

However, it appears that a perpendicular angle is the most desirable option for obtaining a more accurate reading, and an angle of more than 60° can result in a critical loss of information. Considering the anatomical structure of the human body, new techniques, such as 3-D infrared, may help to reduce the influence of the angle of view [432].

3.3.4. Camera features

Currently, IRT camera features are not comparable with those of previous decades. Among the great number of features, a subset may be important to the reading quality and the application of IRT on humans.

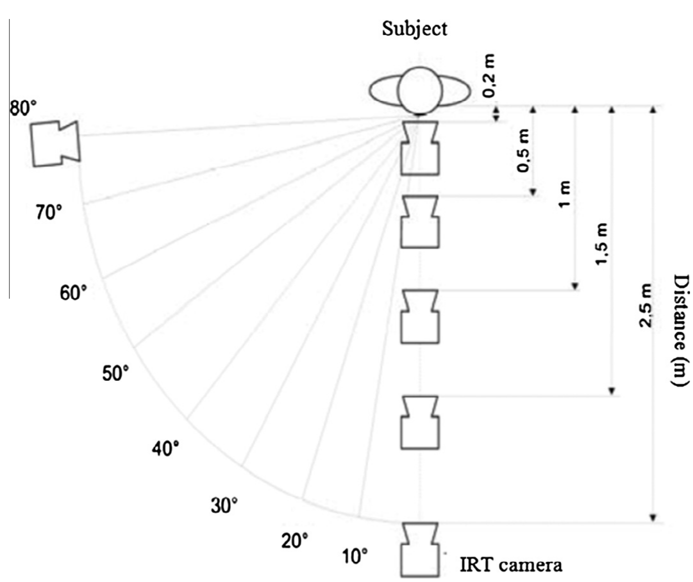

Fig. 13. Representation of different distances and angles for recording IRT images (adapted from Tkacova et al. [425]).

3.3.4.1. Temperature range. IRT cameras are able to identify temperatures between a certain range of temperatures. The variety of application fields has forced IRT camera manufacturers to increase the range from −20 °C to 3000 °C. To our knowledge, no study has determined the influence of using different temperature ranges to measure the same object. Nevertheless, due to the small temperature range of human Tsk (approximately 9°), one may presume that a wider temperature range will be less sensitive for measuring humans [158]. We therefore suggest that an optimised temperature range (approximately 20–50 °C) will maximise the sensitivity of the sensor, compared with wider ranges (such as the standard −20 °C to 120 °C in FLIR cameras), which may cause a loss of sensitivity.

3.3.4.2. Resolution. Another interesting feature of IRT cameras is related to their resolution. Considering that each pixel of the thermogram represents one temperature datum, a larger number of pixels (resolution) means more thermal information.

Certain studies, such as the one conducted by Ammer [426], concluded that temperature readings are less dependent on the number of pixels than are other influencing factors, such as room temperature. Cameras with a 320 × 240 pixel resolution are commonly used in scientific works [345,425,427] and may be defined as the minimum resolution for human use. However, the larger the number of pixels, the better the IRT camera. In recent years, manufacturers have been developed high-resolution cameras with up to 1280 × 1024 pixel resolution [1]. These cameras can provide impressive thermograms that are 12 times better that the minimum recommended resolution (320 × 240).

Nevertheless, as for the case of camera distance, the quantity of thermal information depends on the distance from the camera to the body area analysed. Therefore, certain protocols, such as the one from Glamorgan [424], suggest 24 different body views to measure different areas with an appropriate position and size (resolution).

3.3.4.3. Calibration. One of the most critical points about IRT cameras performance with human applications is related to calibration. Due to their potential error measurement (±2% or ±1% in the best cases) and the decline in performance over more than one year, some authors mentioned the importance of controlling the last date of camera manufacturer calibration [421]. Other authors prefer to avoid this potential error by using a constant and known temperature source (black body) into the thermogram. They aim to have a more accurate reference temperature in order to calibrate the camera, or at least to know the difference between the camera measurement and the known temperature source.

Ring and Ammer [3] assert that, despite the internal reference temperature of many current thermal systems, using a reference source for calibration is highly recommended to improve the results of IRT [1,433]. We therefore suggest the use of a calibration source when IRT is used in humans until camera providers improve the imager's accuracy within the 20–50 °C range.

Since this system could be both expensive and unavailable for a regular use, Plassmann and collaborators [421] described 5 simple procedures to monitor the correct performance of an infrared camera, and thus to detect any changes that could inform us about the need for maintenance and expert calibration. The tests are: Start-up drift, Long-term drift, Offset variation over temperature measurement range, Image non-uniformity and Thermal flooding effects.

3.3.5. ROI selection

One of the most controversial points regarding IRT applications in humans is the selection of the Regions of Interest (ROI). Many IRT studies have developed their own criteria for creating and selecting ROIs. Even though protocols, such as the one used by the Glamorgan group [424], have used standardised ROIs, there is a lack of consensus among researchers.

ROI selection is also a key factor when bilateral areas of the body are compared [53,89]. Certain authors have developed procedures, such as external markers, to improve ROI selection [48,290,382,408,434–436]. Others, however, such as Ferreira et al. [64] decided to avoid any markers around the ROI to avoid temperature changes that may have been due to conduction. In some diagnosis applications, computer simulation and segmentation has been used to improve the ROI selection [178,437,438].

The controversy around of ROI selection is based on the manual procedure that is required to create ROIs. As for reliability, we observed that the ICC results (intra- and inter-examiner Correlation Coefficient ICC) were often suboptimal, due to factors that depended on the ability of the observer to manually select the ROI [3,9]. To improve reliability and to open up the possibility of comparing IRT results among studies, we suggest the development of automatic and objective procedures to select the ROI. In this sense, software solutions with automatic ROI selection features would be a first step, such as the ones proposed from the research group of the Technical University of Madrid [414], the Loughborough University [439], the University of Porto [349,350], the Polytechnic Institute of Leiria [440] or the Federal University of Minas Gerais [348].

3.3.6. Software

As some authors showed, there are different methods, algorithms and software to obtain the final temperature data from a thermal image [4,6,35,100,348,439–448].

Plassmann et al. [421] described a battery of calibration tests using four different thermal imaging cameras. They obtained different thermal results measuring the same object. That could be explained by calibration drifts, but also by different image processing algorithms. Therefore, it is important to know the measurement software used, and also the image processing methods and thermal image formats, because they could influence the thermal results.

Vardasca and collaborators [449] have recently described the characteristics of the majority of IRT analysis software in the market. Some of them use different procedures to extract the thermal data, and most of them, as the IRT cameras, were not designed for being used specifically with humans. Despite some projects in the previous years [441,450–452] bigger efforts should be made by manufacturers, researchers and health professional to define a common modality of medical thermal imaging, as DICOM standard [453]. Based on a consensus, future IRT software and cameras should be designed specifically for the application on humans, with standard processing methods that will make easier the use of IRT regardless of the manufacturer or software used. In addition, it will enforce the credibility of IRT and the spread of its used on human applications.

3.3.7. Statistical analysis

Finally, another important factor that is generally ignored is based on the analysis of the IRT data. The aim of this section is not to examine the possible statistical analyses that can be performed on IRT data, which depends on the design of the study and the criteria of each researcher, but to evaluate the influence of the use of different measurement units or strategies to present the IRT results.

The majority of authors have used averaged ROI temperatures to express their results. This is logical given that these values represent the mean temperature of each ROI. However, average values may occasionally have errors given that the body areas are traced manually. When ROIs are manually selected, they can include certain pixels from the background or from the borders of the ROI, which may exhibit lower temperature values. Thus, the average temperature of the ROI would be lower than the actual value. In these cases, the use of maximal temperatures may be a solution.

In this sense, a recent study of Ludwing and his collaborators [387] presented a critical comparison between the methods mainly used in the literature, i.e., average and maximal temperature. They found a high correlation between both methods, concluding that they can equally represent temperature trends in cutaneous thermo-graphic analyses. Nevertheless, other authors continue to use both methods to better illustrate skin thermal behaviours [60].

Other authors, such as Vainer [371], have used histograms to represent the data distribution and to detect possible errors. Deng and Liu [35] proposed a mathematical modelling of IRT that was based on statistical principles. The majority of the standardisation efforts [416,421,424] are based on reducing the influence of the improper analysis of IRT data. Future efforts may be directed to normalise thermal results by correcting for the influence of these factors, making the use of IRT on humans a more objective process and allowing for the comparison of different subjects (or the same subject over time) independently of environmental, individual and technical factors.

4. Conclusions

The number of the factors that affect the skin temperature (Tsk) in humans is tremendously large. The infeasibility of controlling for all of these factors could be considered one of the weakest points of infrared thermography (IRT). Therefore, this review proposes a comprehensive classification of all those factors in three primary groups: environmental, individual and technical factors.

The potential and increasing interest in the new applications of IRT on humans require an effort: firstly, to further investigate and determinate the unspecified influence of most of the factors on skin temperature; and secondly, to improve this classification with new references and factors.

It is almost impossible to control for all the factors, but only by going deeper in the knowledge of them could help us to avoid their influence or, at least, to know how important they are and to assure a correct use of IRT.

Conflict of interest

The authors declare that there are no conflicts of interest.

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