
Potential Errors in Mean Skin Temperature Calculation Due to Thermistor Placement as Determined by Infrared Thermography

125

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Contents

1	Introduction	1319
2	Neural Control of the Skin Surface	1320
3	Mean Skin Temperature Calculations	1320
4	Thermographic Measurements of the Skin Surface	1323
5	Summary	1326
	References	1327

Keywords

Mean skin temperature • Thermistor probes • Thermography • Infrared imaging • Temperature • Isotherms

1 Introduction

The skin is the largest organ of our body covering approximately 6 m² and providing us with a waterproof protective barrier between our body structures and the environment. However, as a thermal interface, the skin is remarkably adept at managing heat transfers between the metabolic core and the environmental conditions. In cold environments, vasoconstriction of the blood flow within the skin layers functions as an outer body insulator, protecting the core organs from hypothermia. In hot environments, blood flow can be dramatically increased to the skin to transform the tissue into a surface radiator that encourages heat transfers into the environment. The ratio of radiant heat emitted is 0.98 as compared to a black body perfect emitter of 1.0 (Flesch 1985), with no wavelength differences observed between skin colors as detected by infrared imaging (Jones and Plassmann 2008). Thus, the skin can be

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thought of as a thermal chameleon, which alters its function in response to the core-environment heat transfers to provide precise core temperature regulation maintained within a small critical survival zone.

2 Neural Control of the Skin Surface

Neural vasomotor control of the vascular topography within the cutaneous skin layers regulates the appropriate core to skin to environment heat transfers for thermoregulation. The reflex neural regulation modulates the blood flow by way of sympathetic vasoconstriction or vasodilation of the arterial branches that feed the transverse (perforator) vessels which culminate in numerous cutaneous circulatory plexus. Further blood flow regulation occurs in the acral tissue regions (finger/toe digits, ears, nose, cheeks, lips, palmer surfaces of the hand and feet) that are structurally supplied with arteriovenous anastomoses (AVAs). The AVAs are thick-walled, low-resistance vessels that have a direct vascular pathway between the arterioles and venules that regulates plexus blood flow by sympathetic adrenergic vasoconstrictor activity. In the nonacral tissue regions (legs, arms, and chest), blood flow is under the dual control of adrenergic (vasoconstriction) and noradrenergic (vasodilation). For a more in-depth review of the regional sympathetic reflex regulation and skin blood flow, the reader is directed to Johnson and Proppe (1996), Charkoudian (2003), and Pascoe et al. (2006). It is important to recognize these differences in regional blood flow regulation when investigating, measuring, or interpreting the skin temperature surfaces across the various regions of the body.

3 Mean Skin Temperature Calculations

An understanding of the dynamic responses of the skin to internal and external thermal environments and measurements of a mean skin temperature has been a challenge due to the skin's contoured surface area and the constraints of the equipment used to measure the skin surface. The earliest published skin temperature measures were made by Davy in 1814 by holding a thermometer against the skin surface (Burton 1934). The advent of the skin thermocouple at the turn of the century provided greater measurement accuracy, improved testing procedures, and has been the dominant measurement device over the past century.

A "precise" mean skin temperature would require an accurate measurement device and would be derived from an infinite number of body temperature points. All mean skin temperature formulas rely on the assumption that a finite number of skin temperature measures can provide a correct and reliable estimate of mean skin temperature (Teichner 1958). Thermistor measures also assume that areas within the body regions are homogeneous in temperature and representative of the mean skin temperature for that surface area. Intuitively, the more sites a researcher measures, the more representative and reliable the measure of mean skin temperature will be for either regional or whole-body measures. To address this issue, Winslow et al. (1936) produced pivotal research that examined the convective and radiant exchanges of humans under varying environmental conditions. From this research, it has been advocated that 15 recommended sites could provide a "reasonable" maximum for conducting investigations related to the thermal exchanges from the skin surface area. The 15 recommended sites are located in seven regional areas defined as (Fig. 1):

$$\begin{aligned} \text{Mean } T_s = & T_s \text{ Head}(A + B + L)/3 \\ & + T_s \text{ Arms}(D + F)/2 + T_s \text{ Hands}(G) \\ & + T_s \text{ Trunk } (C + E + M + N)/4 \\ & + T_s \text{ Thighs } (H + P0)/2 + T_s \text{ Legs}(J + Q)/2 + T_s \text{ Feet } (K) \end{aligned}$$

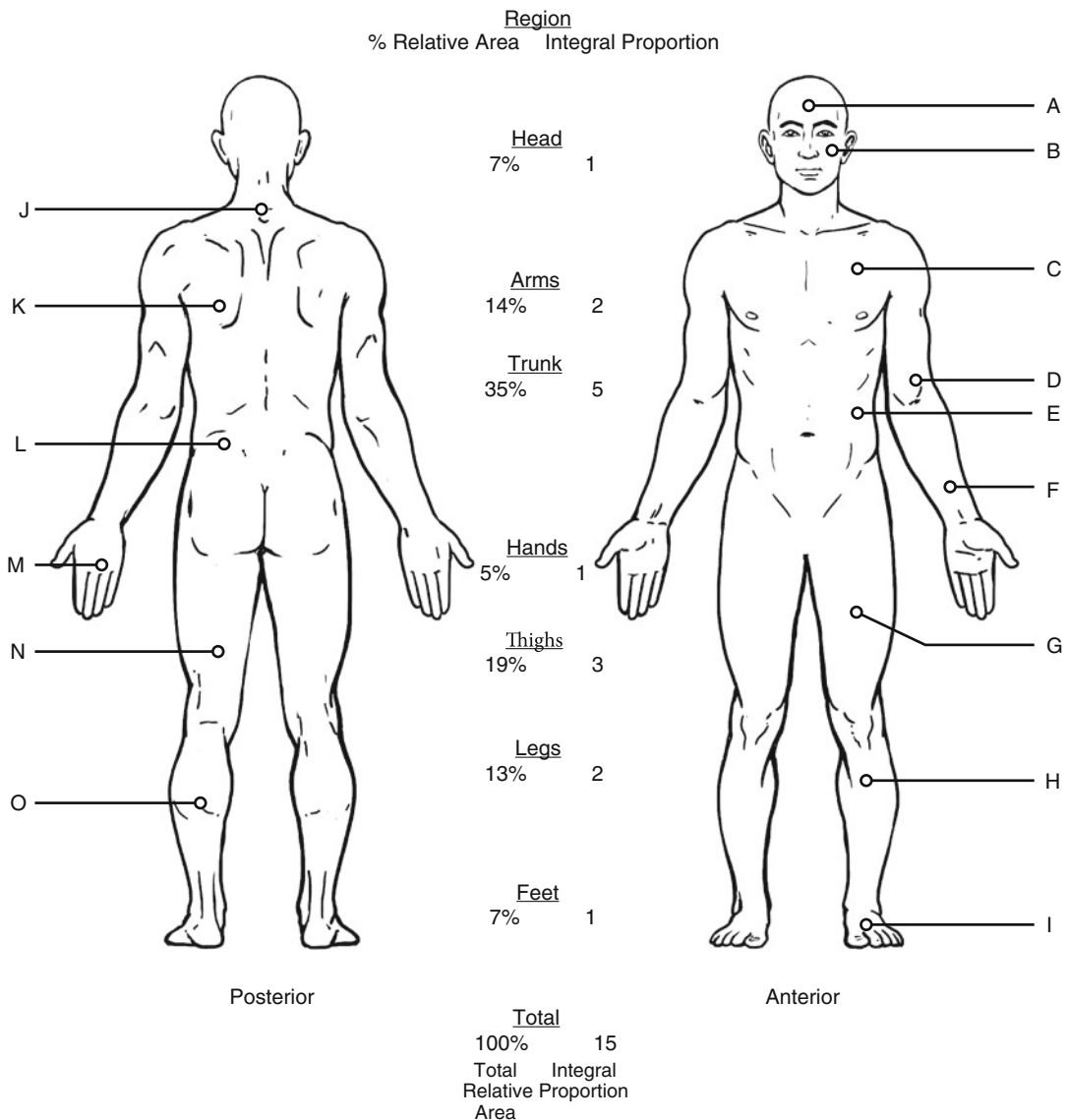


Fig. 1 Site locations, percent of relative area, and approximate integral proportions. Illustration of the 15 “optimal” measurement sites (Image drawn by Jason Adams, Auburn University)

This has been identified as the “optimal method” to determine whole-body mean skin temperature and the standard method used to compare the “accuracy” of other proposed formulas. The “accuracy” of the estimated mean skin temperature formula is determined by the agreement frequency percentage, which calculates the number of values that are within $\pm 0.2\text{ }^{\circ}\text{C}$ when compared to standard measure, where the $0.2\text{ }^{\circ}\text{C}$ allows for

the error of the thermocouple device measurement. Using the same 15 sites, Winslow et al. (1936) proposed that the seven DuBois regions could be reduced to four by combining the arms and hands into the upper extremity and combining the thighs, legs, and feet into the lower extremity.

The research literature has focused on four basic formula approaches: (1) unweighted

average of the sites recorded; (2) weighted formulas based on regional surface averages as defined within population norms; (3) variable weighting based on individually determined surface areas, often determined by the DuBois linear formula; and (4) weighted formulas that incorporate factors that describe both the surface area and the thermoregulatory response to thermal stimuli (Nadel et al. 1973; Crawshaw et al. 1975). This fourth approach recognized that while the surface areas of the various regions help to explain the exposed surface available for heat exchange (conduction, convection, and radiation), differences in regional blood flow, temperature, and sweat gland distribution that contribute to measurable differences in the regional area's ability to dissipate heat through evaporation may not be adequately expressed. Comparative evaluations for various formulas used for mean skin temperature calculations can be found in the following research articles: Mitchell and Wyndham (1969), Lund and Gisolfi (1974), Olsen (1984), and Choi et al. (1997).

Due to the complexity of using 15 site measures, researchers have investigated the validity of monitoring fewer sites from which numerous mean skin temperature formulas have emerged. Mean skin temperature formulas have been devised using 3–15 measurement sites. Under resting conditions, the core environment is often considered homeothermic where the regional peripheral blood flow and temperatures are variable (poikilothermic) and more dependent upon environmental conditions. In colder external environmental conditions, regional skin temperatures are more heterogeneous, and variances across the region can be substantial. In warmer conditions, the skin temperature is more homogeneous and fairly consistent across the surface area. According to prevailing environmental conditions, some researchers have altered the number of measurement sites for the sake of convenience and reduced data handling to avoid measurement situations that would interfere with the research variables. Olsen (1984) used stepwise regression analysis of more than 800 tests from which he concluded that in warm environments 2–4 sites may be adequate, neutral conditions would

require 4–8 sites, and cold environments would require between 8 and 12 sites to demonstrate a high degree of accuracy. Other researchers (Teichner et al. 1958; Veghte 1965; Jirak et al. 1975; Olsen 1984) have analyzed multiple data sources and have stated that at least six to seven sites need to be measured to assure accuracy of the estimated mean skin temperature. Some of the increased variance in regional skin temperatures in the cold can be attributed to the distribution of subcutaneous fat often associated with lower temperatures in areas of greater fat disposition (Livingston et al. 1987). Furthermore, the external environment, exercise metabolism, and clothing create an insulation effect (clo) that strongly influences thermal comfort and creates a microenvironment and thermal barrier that can alter or inhibit the skin surface thermoregulatory responses (Mairiaux et al. 1987; Mehnert et al. 2000). It is also important to recognize that these factors strongly influence the “accuracy” of mean skin temperature measures as determined by the agreement frequency percentage calculation such that a formula could be expected to perform differently under varying conditions, especially environmental temperature.

Potential errors in probe measurement can be attributed to poorly defined probe locations, regional point-to-point variations in temperature, different assigned numerical factoring values that try to account for regional contributions to the thermal status of the individual, and discrepancies created when comparing weighted calculations to the proportional unweighted measures of mean skin temperature. The regional point-to-point variation will be greatly influenced by the environment, where the magnitude of temperature variations has been reported from 7.2 °C to 3.6 °C (Jirak et al. 1975; Firm et al. 1990; Hunold et al. 1992) and deviations of microcirculation in the skin of 300 % within a few centimeters (Hunold et al. 1992). The accuracy of the probe, probe shape, mounting pressure, and adjoining wiring and the microenvironment created by skin surface attachment have provided methodological challenges. However, the thermocouple probe is still the favorite device for skin temperature measures under clothing.

4 Thermographic Measurements of the Skin Surface

In the 1960s, the development of infrared thermographic devices provided researchers with a method of obtaining a noncontact “thermal map” or thermal pictures of the skin surface area. In principle, this device detects the heat that is emitted (reminder: skin emissivity is 0.98) from the skin surface which greatly increases the number of measurement sites from a few probes to more than 10,000 digital pixel temperature-imaging points. The noncontact image removes researchers’ concern over the influence of probe attachment to skin temperature measures while providing a very sensitive increment of measure (0.05 °C). From these images, thermography imaging programs can quickly provide the mean, high, low, and standard deviation of the selected skin surface region. While this imaging may appear to provide all thermal points of interest, there may be a 10 % loss of image accuracy around the border of the body image (projection angle more than 45°) and another 10 % that may be influenced by a thick hair cover (Choi et al. 1977). Additionally, the detection of heat emitted from the skin using infrared thermography is altered by clothing, more specifically the ability of heat transfers to pass through the clothing fabric.

The measured skin surface temperature is a combination of radiant heat from the core and environment and the influence of convective air movements, evaporative cooling during sweating, and conductive heat transfers when the skin is in contact with other surfaces. The radiant source of heat coming from the core is delivered to the skin via peripheral blood flow into the skin vascular plexus. Infrared imaging does not measure blood flow, but the skin temperature measures are strongly correlated to the anatomical distribution and blood flow to the surface area (Fig. 2).

These thermatomes, skin surface temperature patterns, allow the researchers to identify and understand the temperature distribution across the skin surface area, which negates the problem of probe placement. Within regional skin surface areas, the thermal image will have distinct areas

with the same temperature (isotherms). These isotherms represent the blood flow distribution to the skin vascular plexus and the conduction of heat to the adjacent skin tissue layers. Within thermocouple research literature, researchers have observed regional skin surface areas that have a homogeneous temperature distribution that may practically be used to estimate the mean skin temperature of a region. This depends upon the proportional size of the isotherm in the region and the potentially sizeable variances in tissue temperatures across the skin surface that may shift the mean away from the isotherm mean temperature. These isotherms can change in accordance to exposures to varying environmental temperatures (see Fig. 3; Livingstone et al. 1988; Hunold et al. 1992), with greater heterogeneity in the surface temperatures observed when the skin is exposed to colder environments. As such, a same site probe location can provide discrepant measures due to the varying distribution of skin temperatures and fluctuating isothermal patterns.

Thermography is more adept than thermocouples when observing and measuring differences in local skin temperature as a result of radiant heat transfers due to posture and adjoining body parts (arms and torso) and the impact of convective air flow created by movement (mostly arms and legs). Additionally, the importance of the acral regions in heat transfers that modulate thermoregulation cannot be overlooked. As an example, if you feel hot while in bed at night, the simple act of sticking a foot outside of the bed covers changes your thermal status. A single thermal probe is unlikely to adequately describe the thermal response of acral regions (e.g., hands, feet), whereas thermography views the entire skin surface thermal response.

To understand the variances in skin temperature, Pascoe et al. (2012) investigated the mean skin temperatures within body regions in men and women while exposed to three environmental conditions (20, 30, 40 °C; all trials at 40 % relative humidity). Participants equilibrated on separate days within an environmental chamber for 20 min prior to thermographic measurements. The regional skin temperatures were determined from the mean temperature calculated (thermal image program)

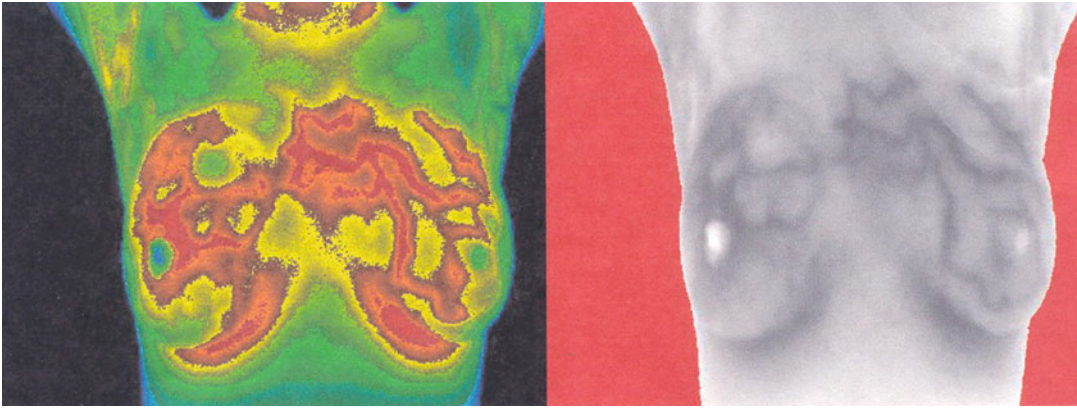


Fig. 2 Vascular image and thermal image. Images depicting the close correlation between the skin vasculature and skin temperature (Image provided by Dr. Robert Ensley)

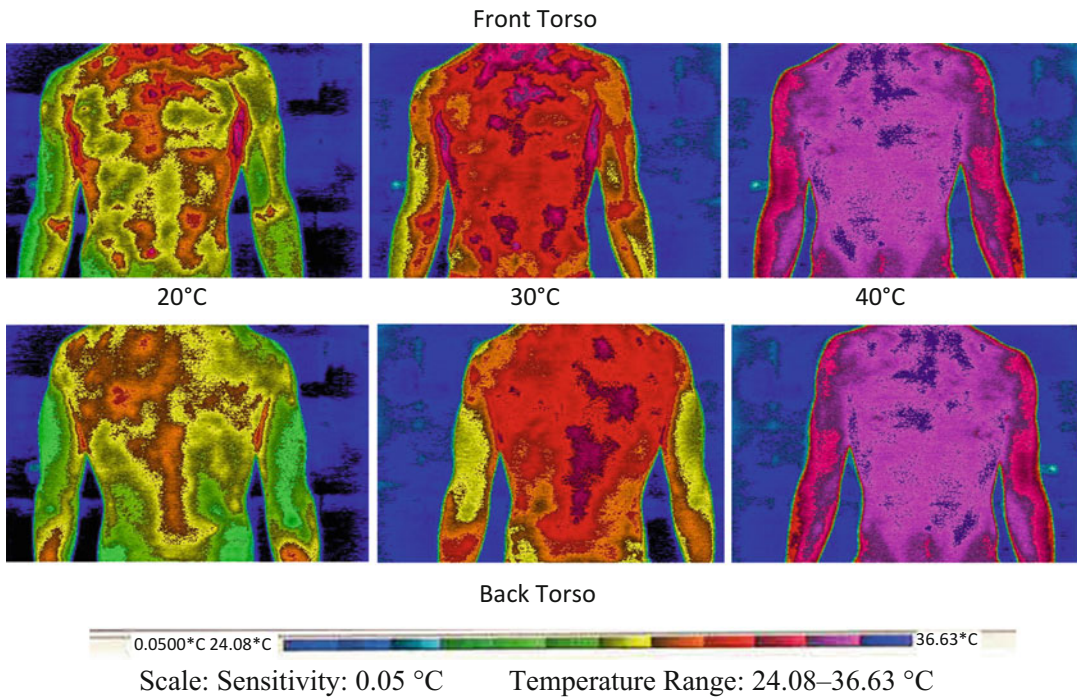


Fig. 3 Isotherm images. Images taken at 20, 30, and 40 °C to illustrate the different patterns in the thermal isotherms (Image taken by Khalil Lee, Vincent Santucci, and David Pascoe)

from the combined pixels within each regional surface area. No significant differences were found between men and women, so their data were combined. The regional skin temperatures in Figs. 4 and 5 demonstrate several key points:

1. The distribution and differences in regional thermal skin temperatures are linked to the environmental conditions.
2. The torso regional temperatures show a more homogeneous distribution when compared to

Fig. 4 Mean skin temperatures of torso across environmental conditions. Mean skin temperature of torso regions at 20, 30, and 40 °C as determined from thermographic images. *RS* right scapula, *LUC* left upper chest, *RA* right arm, *LLB* left lower back

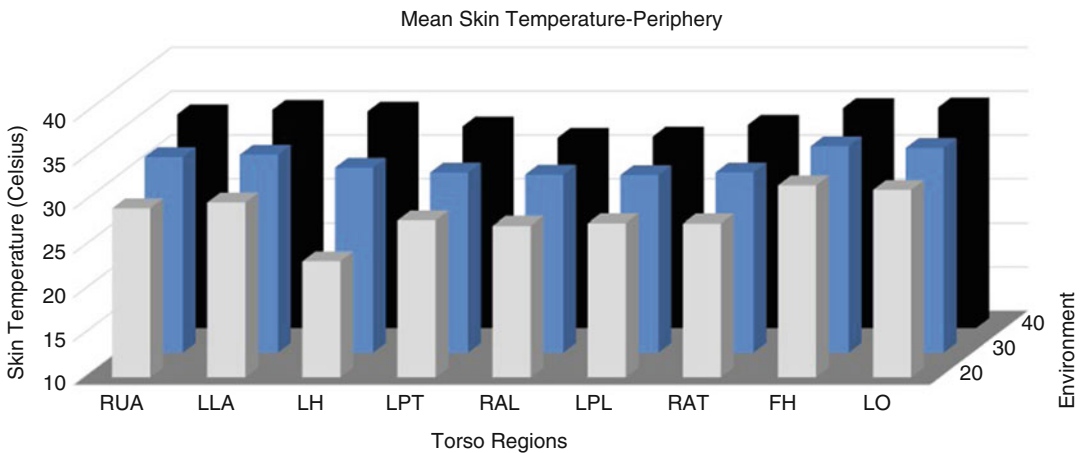
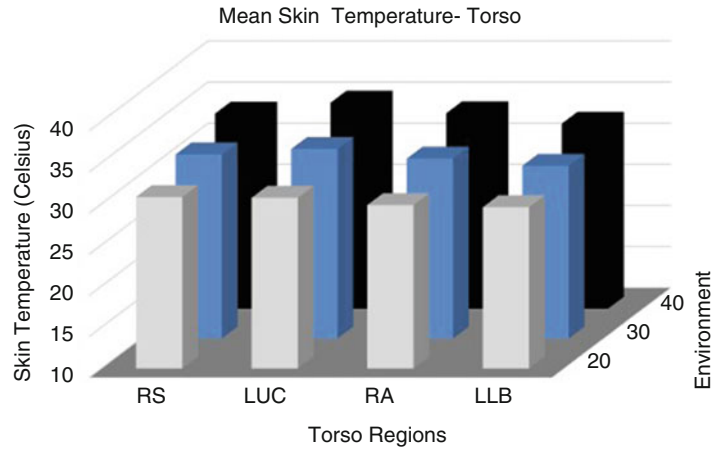


Fig. 5 Mean skin temperature of periphery across environmental conditions. Mean skin temperature of periphery regions at 20, 30, and 40 °C as determined from thermographic images. *RUA* right upper arm, *LLA* left lower arm,

LH left hand (posterior view), *LPT* left posterior thigh, *RAL* right anterior leg, *LPL* left posterior leg, *RAT* right anterior thigh, *FH* forehead, *LO* lower occipital

heterogeneous thermal responses of the peripheral regions.

3. The greater variance of temperatures within the extremities can be attributed to the heat transfer properties of the acral regions (mostly hands and feet), which explains why the skin in the proximal portions of the limbs responds differently to the same environmental stressor (Clark). This observation illustrates the importance of the arteriovenous anastomoses within the acral regions for heat exchange and thermoregulation.
4. The variance in the temperature measures within and between regions suggests the

potential for research error that can be observed when using formulas that vary in measurement site location, exposures to different environmental conditions, and the number of sites.

This potential error may be compounded by adding a “weighting” factor whose estimate of the mean skin temperature accuracy, as determined by the agreement frequency, varies according to environmental conditions and whether the individual is nude or clothed (Teichner 1958; Choi et al. 1977; Livingstone 1987).

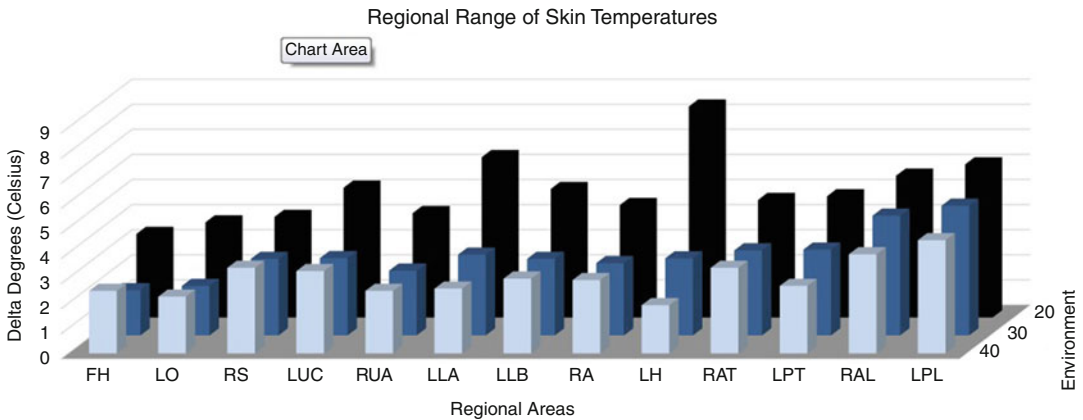


Fig. 6 Range of regional temperatures across environmental conditions. Variance of skin temperatures for optimal regions at 20, 30, and 40 °C as determined from thermographic images. *RUA* right upper arm, *LLA* left lower arm, *LH* left hand (posterior view), *LPT* left posterior

thigh, *RAL* right anterior leg, *LPL* left posterior leg, *RAT* right anterior thigh, *FH* forehead, *LO* lower occipital, *RS* right scapula, *LUC* left upper chest, *RA* right arm, *LLB* left lower back

In Fig. 6, the range of temperatures within a region (high minus low measurement) demonstrates the variance in temperatures within and between regional skin temperatures surfaces. The figure clearly depicts the greater variance in regional areas during the colder exposure. This is consistent with the research literature and supports the need for using more thermistor probes when investigating mean skin temperature in colder environments (Olsen 1984). Unlike thermistors where a site may or may not represent the regional mean, thermographic skin temperature measures are able to capture all pixel sites from which a mean temperature is determined.

It is important to remember that the skin serves as an interface between the core thermal environment and the external environmental conditions. A majority of the research studies investigating mean skin temperature have been performed in the nude during resting conditions. Clothing can interfere with the normal regulatory processes, often creating a microenvironment that increases both temperature and humidity. The increased humidity reduces the skin to air vapor pressure which interferes with evaporative cooling. The wearing of loose clothing may reduce some of the thermal stress through clothing movement (pumping action) that increases the convective air movements. The insulation effect of clothing,

clothing layers, and location of clothing all affect the distribution of skin temperatures (Nielsen and Nielsen 1984). In the clothed individual, the ability to access the skin surface area for infrared imaging may dictate whether the researcher uses thermistors or thermography. During work/exercise, the increase in the metabolic heat production must be regulated by skin heat transfers. Using thermography, Clark et al. (1977) observed an initial drop in skin temperatures with the initiation of exercise with a subsequent increase in skin temperatures over active muscle areas. They concluded the change in distribution patterns from the resting state were due to the direct heat transfer from the muscle tissue to the skin surface. While sweating would be expected to provide evaporative cooling, the wiping of sweat from the skin did change the thermal pattern. This demonstrated that the wetness of the skin does not significantly influence the skin surface emissivity.

5 Summary

When reviewing and interpreting the literature on mean skin temperature, the reader must be cognizant of the experimental influence of the following factors:

1. Measuring device and measuring accuracy: thermistor probes, attachment, infrared thermography-defined surface area, and sensitivity;
2. Environmental conditions: temperature, humidity, wind, and direct/indirect radiant heat sources [sunlight, incandescent lights, and heaters];
3. Activity level of the participants: passive or exercising [intensity, duration, mode of exercise, exercise or body movements that increase the convective air flow across the skin surface];
4. Layers of clothing, clothing fit, and heat transfer and moisture transport properties of fabric; and
5. Choice of mean skin temperature formulas: number of sites being evaluated, weight or unweighted.

All of these conditional factors explain the differences observed in the measures of mean skin temperature and research citations, but these factors also complicate our understanding of the thermoregulatory responses observed through the modulation of perfusion to our interactive skin tissue.

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