

NON-INVASIVE BIOPHYSICAL EVALUATION OF MICROCIRCULATION USING THERMAL IMAGING IN YOUNG ADULTS

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Abstract. Microcirculation plays a fundamental role in tissue metabolism, thermoregulation, and vascular homeostasis. Early functional disturbances in microvascular regulation often remain clinically undetected, particularly in young adults, despite their potential contribution to long-term cardiovascular and metabolic risk. From a biophysical perspective, alterations in microcirculatory function are closely linked to changes in heat transfer and surface temperature distribution.

This study investigates the use of thermal imaging as a non-invasive biophysical method for evaluating microcirculatory function in young adults. Skin surface temperature patterns were analyzed to assess peripheral perfusion and microvascular regulatory behavior under resting conditions. Emphasis was placed on spatial and functional thermal characteristics rather than absolute temperature values. The analysis revealed heterogeneous thermal patterns indicative of early microcirculatory imbalance, even in individuals without apparent clinical symptoms. The findings suggest that thermal imaging provides sensitive biophysical markers of functional microcirculatory alterations. Application of this approach may enhance early detection of microvascular vulnerability and support preventive assessment strategies in young adult populations.

Keywords. Biophysics; microcirculation; thermal imaging; non-invasive diagnostics; young adults

Introduction

Microcirculation is a critical component of the cardiovascular system, responsible for delivering oxygen and nutrients to tissues, removing metabolic byproducts, and maintaining thermal balance. Functional integrity of the microvascular network is essential for tissue homeostasis, yet early disturbances in microcirculatory regulation often remain clinically undetected. In young adults, such alterations may develop silently and precede structural vascular changes or overt disease manifestations.

From a biophysical perspective, microcirculatory function is closely linked to heat exchange processes at the tissue level. Blood flow through superficial microvessels directly influences skin temperature distribution, making thermal patterns a functional reflection of microvascular activity. Changes in vasomotor tone, capillary recruitment, or perfusion stability may therefore manifest as alterations in surface temperature dynamics rather than as abnormalities detectable by conventional clinical methods.

Young adult populations are increasingly exposed to factors that may compromise microcirculatory regulation, including sedentary lifestyle, psychosocial stress, environmental heat, dehydration, and irregular circadian rhythms. These influences can impair endothelial

function and autonomic control of microvessels without producing immediate symptoms. As a result, routine diagnostic approaches, which typically focus on systemic parameters or invasive techniques, may fail to capture early functional microvascular imbalance.

Thermal imaging has emerged as a promising non-invasive technique for assessing microcirculatory function by visualizing spatial and temporal variations in skin temperature. Unlike point-based measurements, thermal imaging provides a comprehensive representation of peripheral perfusion and allows evaluation of regulatory efficiency across larger anatomical regions. Biophysical interpretation of thermal patterns emphasizes functional behavior and adaptability of microcirculation rather than absolute temperature values.

The present study aims to evaluate microcirculatory function in young adults using thermal imaging within a biophysical framework. By focusing on non-invasive assessment of heat distribution and microvascular regulation, this work seeks to contribute to early identification of functional microcirculatory imbalance and to support preventive strategies aimed at preserving vascular health in young populations.

Main Part

From a biophysical perspective, microcirculation represents a highly dynamic regulatory system that integrates vascular tone, endothelial function, neural control, and local metabolic demands. The efficiency of this system determines tissue perfusion, oxygen delivery, and heat exchange at the microscopic level. Even subtle disturbances in microvascular regulation may lead to functional heterogeneity in blood flow distribution, which precedes structural vascular damage and clinically detectable pathology.

Heat transfer in biological tissues is closely coupled with microcirculatory blood flow. Perfused regions facilitate convective transport of heat from deeper tissues to the skin surface, resulting in higher local temperatures, whereas reduced perfusion leads to relative surface cooling. Consequently, spatial and temporal variations in skin temperature can be interpreted as indirect indicators of microcirculatory behavior. From a biophysical standpoint, these thermal patterns reflect the integrated outcome of vasomotor activity, capillary recruitment, and perfusion stability.

Thermal imaging enables visualization of infrared radiation emitted by the skin surface, generating detailed temperature maps that capture microcirculatory-related heat distribution. Unlike invasive or contact-based techniques, thermal imaging does not disturb local blood flow and allows assessment of large anatomical regions simultaneously. Parameters such as thermal symmetry, spatial heterogeneity, and temporal fluctuation provide functional insight into microvascular regulation rather than absolute blood flow values.

In young adults, early microcirculatory disturbances may arise due to lifestyle and environmental influences, including physical inactivity, psychosocial stress, dehydration, and exposure to thermal load. These factors can impair endothelial responsiveness and autonomic control of microvessels without producing immediate clinical symptoms. As a result, functional alterations in microcirculation may accumulate silently, increasing vulnerability to future cardiovascular and metabolic disorders.

Biophysical interpretation of thermal imaging focuses on regulatory efficiency and adaptive capacity of microcirculation. Increased thermal heterogeneity, asymmetry between contralateral body regions, and reduced temporal stability of temperature patterns suggest diminished microvascular adaptability. Such features indicate a transition from flexible physiological regulation toward regulatory rigidity, which may compromise tissue homeostasis under stress conditions.

Thus, thermal imaging serves as a valuable biophysical tool for exploring early microcirculatory dysfunction. By translating surface temperature distributions into functional indicators of vascular regulation, this approach provides a theoretical and analytical foundation for experimental assessment of microcirculatory adaptation, forming a logical bridge to the methodological procedures described in the subsequent section.

Materials and Methods

The study was conducted as a non-invasive biophysical investigation aimed at evaluating microcirculatory function in young adults using thermal imaging. The study population consisted of individuals aged 18–35 years with no diagnosed cardiovascular, metabolic, or peripheral vascular diseases. Participants were recruited from academic and working environments and represented a generally healthy young adult cohort. Individuals with acute illness, chronic inflammatory conditions, dermatological disorders affecting the measurement area, or current use of vasoactive medications were excluded.

All measurements were performed under standardized conditions to minimize external influences on skin temperature and microcirculatory behavior. Participants were examined in a temperature-controlled room after an acclimatization period, during which they remained seated and avoided physical activity. Caffeine intake, smoking, and vigorous exercise were restricted prior to assessment to reduce transient effects on peripheral perfusion.

Thermal imaging was performed using a non-contact infrared imaging system capable of capturing high-resolution surface temperature maps. Images were obtained under resting conditions with participants positioned to allow unobstructed visualization of the selected anatomical regions. Care was taken to ensure consistent camera distance and angle across all measurements. Thermal data acquisition focused on regions commonly used for microcirculatory assessment, allowing evaluation of spatial temperature distribution and bilateral symmetry.

Biophysical analysis emphasized functional thermal characteristics rather than absolute temperature values. Parameters such as spatial heterogeneity, temperature gradients, and symmetry between contralateral regions were analyzed as indicators of microvascular regulation. Increased heterogeneity and asymmetry were interpreted as signs of impaired microcirculatory control and reduced adaptive capacity.

A biophysical interpretative framework was applied to integrate thermal parameters into an overall assessment of microcirculatory function. The analysis focused on system-level behavior of peripheral perfusion, reflecting regulatory efficiency and adaptability. Data interpretation was oriented toward identifying early functional disturbances in microcirculation rather than diagnosing structural vascular pathology.

Results

Thermal imaging analysis revealed measurable functional differences in microcirculatory behavior among young adults despite the absence of clinically evident vascular pathology. Surface temperature distributions demonstrated heterogeneous patterns reflecting variability in peripheral perfusion and microvascular regulation. These differences were most pronounced in regions commonly associated with thermoregulatory control, indicating early functional alterations rather than structural vascular damage.

Quantitative characteristics of thermal patterns are summarized in **Table 1**. Individuals exhibiting signs of microcirculatory imbalance showed increased spatial temperature heterogeneity and reduced bilateral symmetry compared with participants demonstrating stable

microvascular regulation. Such features suggest diminished regulatory efficiency and reduced adaptive capacity of the microcirculatory network.

Table 1. Thermal imaging indicators of microcirculatory function

| Parameter | Microcirculatory imbalance | Stable microcirculation |
|-------------------------------------|----------------------------|-------------------------|
| Mean surface temperature | Variable | Stable |
| Thermal heterogeneity | Increased | Low |
| Bilateral symmetry | Reduced | Preserved |
| Temperature gradients | Pronounced | Minimal |
| Functional microcirculatory reserve | Reduced | Preserved |

The biophysical interpretation of thermal patterns associated with microcirculatory regulation is illustrated in **Figure 1**. Regions with homogeneous temperature distribution correspond to stable perfusion, whereas patchy or asymmetric thermal patterns reflect uneven microvascular blood flow and impaired regulatory coordination.

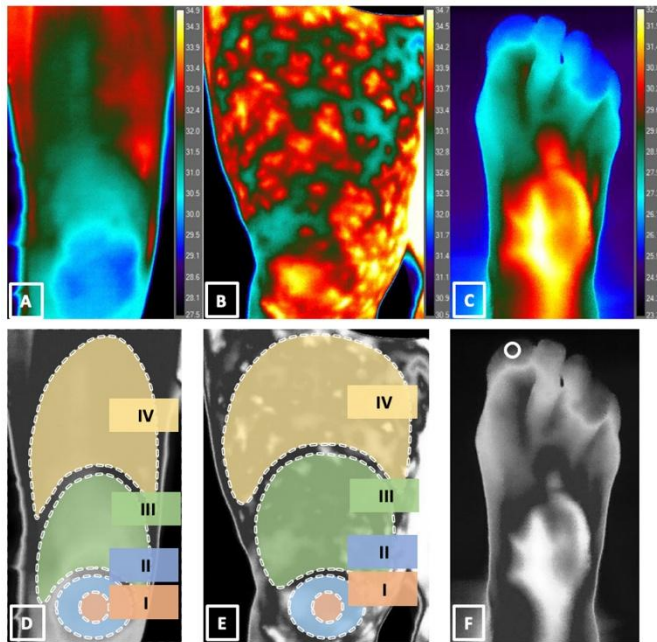


Figure 1. Representative thermal imaging patterns illustrating homogeneous versus heterogeneous surface temperature distribution associated with microcirculatory regulation.

Group-wise comparison of thermal symmetry indices is presented in **Figure 2**. Young adults with microcirculatory imbalance demonstrated greater asymmetry between contralateral regions, indicating altered vasomotor control and reduced microvascular adaptability. In contrast, participants with stable regulation showed near-symmetrical thermal distributions.

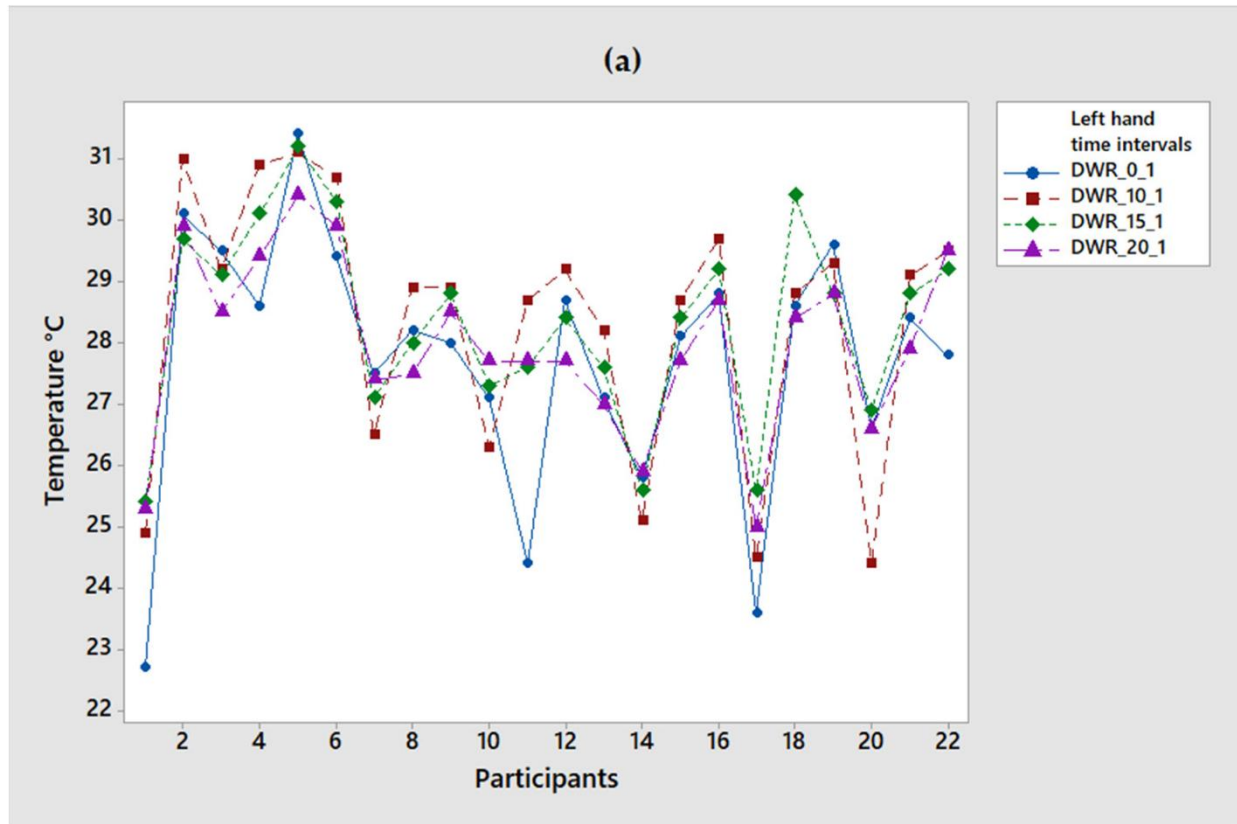


Figure 2. Comparison of bilateral thermal symmetry between individuals with microcirculatory imbalance and those with stable microcirculation.

The relationship between thermal heterogeneity and functional microcirculatory reserve is further illustrated in **Figure 3**. Increased heterogeneity was associated with reduced functional reserve, suggesting that microcirculatory adaptation capacity declines as temperature distribution becomes more irregular. This relationship supports the interpretation that early microcirculatory dysfunction manifests as a functional disturbance in regulatory behavior rather than overt vascular pathology.

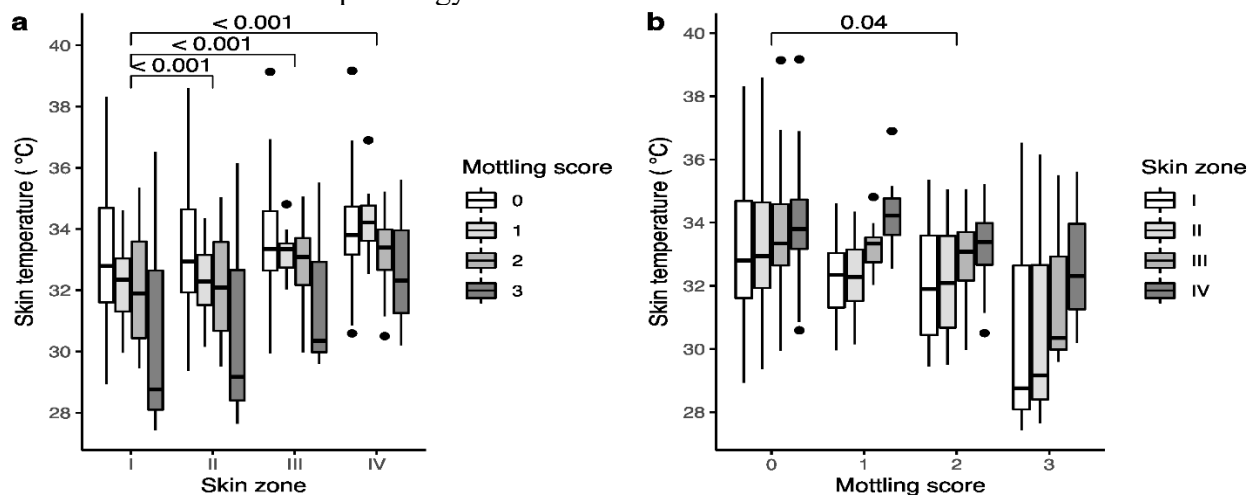


Figure 3. Relationship between thermal heterogeneity and functional microcirculatory reserve based on thermal imaging analysis.

Overall, the results demonstrate that thermal imaging detects early functional alterations in microcirculatory regulation in young adults. Changes in temperature heterogeneity, symmetry, and gradient characteristics reflect reduced regulatory efficiency and adaptive capacity, highlighting the sensitivity of biophysical thermal assessment for identifying microvascular vulnerability prior to clinical manifestation.

Discussion

The present findings indicate that thermal imaging is capable of revealing early functional alterations in microcirculatory regulation among young adults, even in the absence of clinically apparent vascular disease. The increased spatial heterogeneity and reduced bilateral symmetry observed in the Results section suggest impaired coordination of microvascular blood flow rather than structural abnormalities. From a biophysical perspective, such patterns reflect diminished regulatory efficiency within the microcirculatory network.

The thermal patterns illustrated in Figure 1 support the interpretation that homogeneous surface temperature distribution corresponds to stable perfusion, whereas heterogeneous and asymmetric patterns indicate uneven vasomotor control. These observations align with the concept that microcirculatory dysfunction initially manifests as functional dysregulation of blood flow distribution before progressing to detectable structural changes. The reduced symmetry between contralateral regions shown in Figure 2 further emphasizes altered autonomic and endothelial control of microvessels.

The relationship between thermal heterogeneity and reduced functional microcirculatory reserve demonstrated in Figure 3 suggests that microvascular adaptation follows a continuum. As regulatory flexibility decreases, temperature distribution becomes increasingly irregular, indicating a loss of adaptive capacity. This gradual transition from stable to rigid regulation is consistent with biophysical models of vascular control, in which early dysfunction reflects reduced responsiveness to local metabolic and thermoregulatory demands.

In young adults, lifestyle and environmental factors such as physical inactivity, psychosocial stress, dehydration, and thermal exposure may contribute to these early functional changes. Because conventional clinical assessments often focus on systemic or structural indicators, such early microcirculatory disturbances may remain undetected. Thermal imaging, by capturing system-level heat distribution, provides a functional window into microvascular behavior that complements existing diagnostic approaches.

Overall, the close correspondence between thermal imaging features and indicators of microcirculatory reserve supports the value of this non-invasive biophysical method for early detection of microvascular vulnerability. Interpreting thermal patterns within a biophysical framework enhances understanding of microcirculatory adaptation and may inform preventive strategies aimed at preserving vascular health before the onset of overt disease.

Conclusion

The present study demonstrates that thermal imaging provides a sensitive and non-invasive biophysical approach for detecting early functional alterations in microcirculatory regulation in young adults. Changes in surface temperature distribution, increased thermal heterogeneity, and reduced bilateral symmetry reflect impaired microvascular coordination and diminished adaptive capacity, even in the absence of clinically evident vascular pathology.

By interpreting thermal patterns within a biophysical framework, the study highlights that early microcirculatory dysfunction manifests as regulatory imbalance rather than structural damage.

Thermal imaging captures system-level behavior of peripheral perfusion, offering insights into vascular adaptability that are not accessible through conventional diagnostic methods focused on static or invasive measurements.

Overall, the findings support the use of thermal imaging as a valuable tool for early identification of microvascular vulnerability. Incorporation of this non-invasive biophysical assessment into preventive screening strategies may enhance early risk detection and contribute to preserving vascular and metabolic health in young adult populations.

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