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ORIGINAL RESEARCH

Infrared thermography of the quadriceps during early passive recovery (0–6 min) after incremental exercise in professional female volleyball athletes

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Abstract

Background: Infrared thermography (IRT) is increasingly applied to monitor muscle temperature during recovery, offering insight into thermoregulatory and vascular responses after exercise. However, evidence linking early post-exercise skin temperature changes with systemic markers such as oxygen uptake and lactate remains limited. **Objective:** To analyze the early passive recovery behavior of quadriceps skin temperature (0–6 min) after a progressive exercise test in trained female volleyball athletes and examine its association with aerobic capacity and blood lactate. **Methods:** Twenty professional female volleyball players completed a progressive treadmill test until volitional fatigue. Skin temperature of the rectus femoris and vastus lateralis was measured via IRT immediately after exercise cessation (minute 0) and during minutes 1–6 of passive recovery. Aerobic capacity (VO_2peak) was assessed through breath-by-breath gas analysis, and blood lactate was obtained at rest, immediately post-exercise, and at 3 min of recovery. Temperature change (ΔT) and thermal slope (°C·min^{-1}) were calculated. Pearson correlations and multiple regression models were applied. **Results:** Minimal skin temperature change occurred within the first 6 min of recovery. Both muscle regions exhibited high coherence in thermal responses (ΔT and slope correlations r = .76–.91, ps < .001). Neither VO_2peak nor lactate levels significantly predicted thermal behavior (all ps > .05). Early cooling patterns appeared primarily regulated by autonomic vascular adjustments rather than aerobic fitness or lactate kinetics. **Conclusions:** In professional female volleyball players, quadriceps skin temperature remains relatively stable during early passive recovery after incremental exercise, and this response is unrelated to aerobic capacity or lactate removal. Early post-exercise IRT reflects local vasomotor regulation, suggesting that longer monitoring windows and multimodal physiological assessments are needed for a comprehensive evaluation of recovery.

Keywords: thermography, vasodilation, lactates, oxygen consumption, athletic performance, recovery of function, volleyball

Introduction

The assessment of thermal responses after exercise provides valuable insight into cardiovascular and metabolic recovery mechanisms. Thermoregulation depends on efficient heat dissipation through vasodilation, sweating, and increased skin blood flow, which varies according to aerobic capacity and environmental conditions (Otani et al., 2021). In intermittent or high-intensity sports, inadequate heat removal may impair recovery and increase physiological strain even under moderate workloads.

Infrared thermography (IRT) enables non-invasive monitoring of skin temperature (T_sk) as a proxy for regional blood flow and muscular activation (Majano et al., 2023). Jastrzębska et al. (2022) demonstrated that athletes with higher VO_2max (58.3 ± 5.2 mL·kg^{-1}·min^{-1}) exhibited faster post-exercise temperature normalization at the temple region (temperature change –1.2 ± 0.4 °C within 5 min) compared to those with lower aerobic capacity (p < .01), supporting a link between thermoregulation and cardiorespiratory fitness. Similarly, Corral-Pérez et al. (2023) found that older adults with higher VO_2peak (27.8 ± 3.9 mL·kg^{-1}·min^{-1}) showed greater increases in leg T_sk (+1.5 °C immediately post-exercise) and faster return to baseline after 10 min (p = .03), highlighting the influence of fitness on thermal kinetics during recovery (da Silva et al., 2024).

Complementarily, a systematic review by Rojas-Valverde et al. (2021) covering 54 studies (1,216 participants) revealed that post-exercise skin temperature recovery is highly dependent on muscle mass involvement and environmental stress. Average surface temperature drops of 1.5–2.0 °C were typical within 10–15 min of recovery, yet large heterogeneity

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persisted between protocols. The authors emphasized that integrating IRT with physiological measures like VO_2 and blood lactate could improve understanding of recovery efficiency (Rojas-Valverde et al., 2021).

Research on active cooling further supports this link. Otani et al. (2021) tested 10 trained men (age 25 ± 6 y) performing cycling in 33 °C and 65 % humidity. Using a fan-cooling jacket reduced mean T_sk by ~1.8 °C and heart rate by ~10 bpm compared with control ($p < .05$), demonstrating that enhanced evaporative cooling accelerates thermal recovery and mitigates cardiovascular strain. These findings underscore the physiological relevance of thermal slopes and temperature change (ΔT) values in assessing recovery efficiency.

However, despite accumulating evidence, little is known about the relationship between post-exercise T_sk behavior and systemic markers such as VO_2peak and lactate removal in specific muscle regions. Understanding whether surface temperature decline reflects underlying metabolic clearance may inform individualized recovery strategies.

Therefore, the present study aimed to analyze the post-exercise thermal response of the rectus femoris and vastus lateralis following a progressive treadmill test in professional volleyball players. Specifically, it sought to examine the correlation between thermographic parameters (temperature change and slope) and physiological indicators (VO_2peak and blood lactate) during recovery. It was hypothesized that early thermographic behavior (temperature change and slope) would be associated with aerobic capacity (VO_2peak) and lactate concentration during passive recovery.

Methods

Research design

This study employed a cross-sectional experimental design to analyze the physiological responses of professional volleyball players during a progressive treadmill test. Participants competed in the Liga Nacional A1 Femenina, the top division of Chilean volleyball, organized by the Chilean Volleyball Federation. The team regularly qualifies for South American club competitions organized by the South American Volleyball Confederation, and several athletes were current or former members of the Chilean national teams. A total of twenty female volleyball athletes voluntarily participated (age 23.1 ± 5.7 years, body height: 1.73 ± 0.07 m, body mass 75.4 ± 9.4 kg, body fat 34.3% ± 5.6%, muscle mass 28.8% ± 2.6%). All participants were free from musculoskeletal injuries and reported no history of cardiovascular, metabolic, or neurological disorders. Body composition (body fat and muscle mass) was assessed by bioelectrical impedance analysis; here, muscle mass (%) denotes the percentage of total body mass estimated as muscle by the device (seca mBCA Go 525c; seca GmbH).

To minimize external influences, the athletes were instructed to avoid strenuous exercise, alcohol, and caffeine for at least 24 hours before testing. All assessments were conducted at the university's exercise physiology laboratory under controlled environmental conditions (temperature 22–23 °C; relative humidity 50–55%). The study was approved by the Scientific Ethics Committee of Universidad Viña del Mar (Code: R19-02). All procedures adhered to the ethical principles outlined in the Declaration of Helsinki for research involving human participants. Written informed consent was obtained from all participants prior to data collection (World Medical Association, 2025).

Procedures

Aerobic capacity (VO_2peak test)

Cardiorespiratory fitness was evaluated through a linear progressive treadmill test, specifically designed to assess aerobic performance in volleyball athletes. The test was conducted on a h/p/cosmos CosCom V4 treadmill, controlled by the MetaSoft Studio system (MM3 + Treadmill configuration) to ensure standardized speed increments and accurate data acquisition. Respiratory gases were continuously analyzed using a metabolic analyzer METAMAX 3B (Cortex Biophysik GmbH). This device performs breath-by-breath analysis of oxygen uptake (VO_2), carbon dioxide output (VCO_2), and ventilation, providing detailed insight into each participant's respiratory and metabolic response during exercise. The device was properly calibrated and sanitized before each session to guarantee measurement accuracy and hygiene.

The test began with a 2-min warm-up at 4 km·hour^{-1}, after which the speed increased progressively by 1 km·hour^{-1} every minute, maintaining a constant incline of 1% throughout. Participants continued running until volitional exhaustion, defined as the inability to maintain the required speed despite verbal encouragement. During the test, oxygen consumption (VO_2peak), minute ventilation, carbon dioxide production (VCO_2), and the respiratory exchange ratio were recorded continuously and averaged every 15 s. The 3-min time point for lactate collection was selected based on evidence indicating that peak blood lactate concentration typically occurs between 2 and 5 min following incremental exercise.

All assessments were performed under controlled laboratory conditions and supervised by an experienced exercise physiologist. This progressive linear protocol allowed for the precise determination of peak aerobic capacity (VO_2peak) and the identification of ventilatory thresholds, reflecting the participants' efficiency in oxygen utilization during incremental effort.

A capillary blood sample (25 µL) was obtained from the tip of the index finger to measure lactate concentrations at rest, immediately post-exercise (0 min), and after 3 min of recovery. Values were expressed in mmol·L^{-1}. All capillary blood tests were analyzed by Accutrend Plus (Roche Diagnostics).

Thermographic assessment

Infrared thermography, a technique widely applied in sports science to assess physiological responses, performance, and recovery in volleyball players, was performed using a wireless smartphone-based thermal imaging camera (FLIR ONE Edge Pro, Teledyne FLIR LLC; 160 × 120 pixel thermal resolution, thermal sensitivity 70 mK) positioned 1 m from the anterior aspect of the thighs. Images were

captured immediately after exercise cessation (minute 0, with the participant seated at the onset of passive recovery) and at 1, 2, 3, 4, 5, and 6 min during seated passive recovery (Figure 1; Dragoș et al., 2022; Secchi et al., 2019; Zhang et al., 2025).

Regions of interest were defined on the vastus lateralis and rectus femoris muscles using the measurement tools of the FLIR ONE mobile application (Teledyne FLIR LLC). Temperature data were extracted directly from the application and its exported radiometric PDF reports. Skin temperature (°C) was calculated as the mean of each region. Environmental emissivity was set at 0.98.

Thermal slope values (°C·min^{-1}) were estimated by linear regression using the seven recovery time points (0–6 min).

Statistical analysis

Descriptive statistics are presented as mean ± standard deviation. Normality of data distribution was verified using the Shapiro–Wilk test prior to conducting parametric analyses.

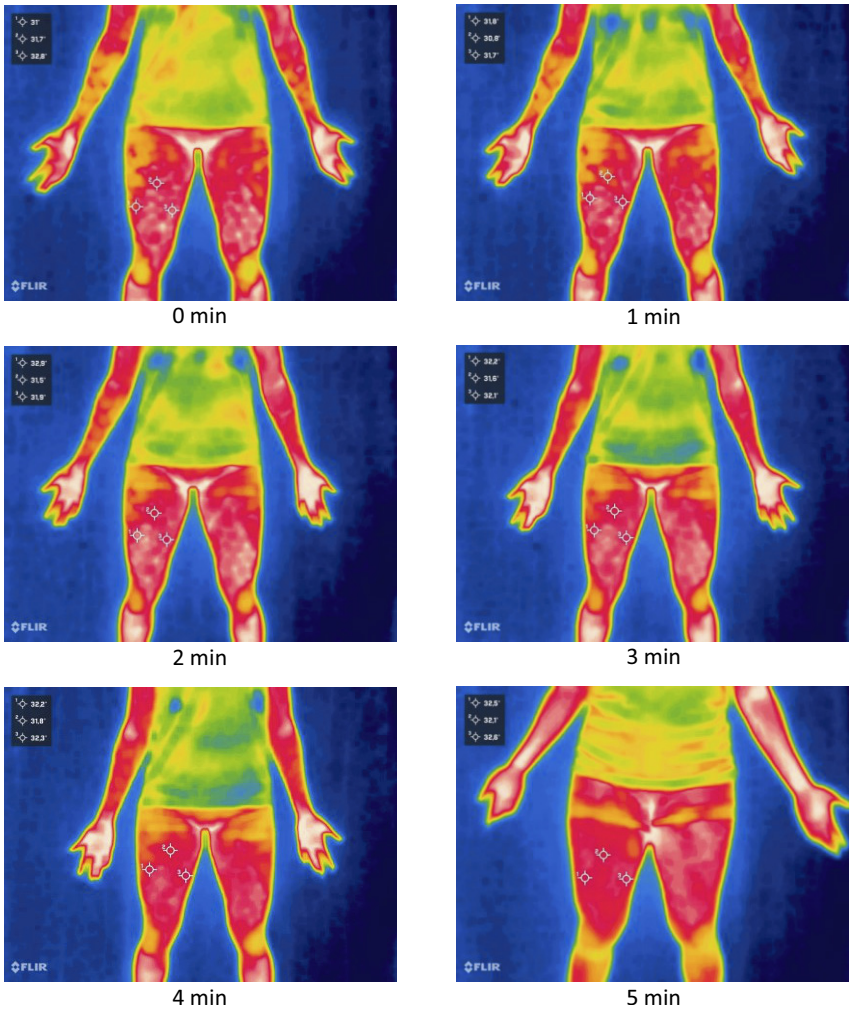
Pearson correlation coefficients were calculated to evaluate relationships among thermal variables and physiological indicators (VO_2peak and blood lactate).

Multiple linear regression analyses were performed to determine whether VO_2peak and post-exercise lactate predicted temperature change (ΔT) or slope (°C·min^{-1}). The significance level was set at $p < .05$. All analyses were performed using jamovi (Version 2.4.12; The jamovi project) and verified with Python (Version 3.12; The Python Software Foundation) with Pandas, Pingouin, and SciPy packages.

Results

Table 1 presents the descriptive statistics of skin temperature measured through thermography in the vastus lateralis and rectus femoris during the recovery period. At rest, mean temperature was 31.28 ± 1.04 °C in the vastus lateralis and 31.01 ± 1.11 °C in the rectus femoris. Throughout the 0–6 min recovery period, temperatures remained remarkably stable, showing only minimal fluctuations and, in some cases, a slight increase, reaching 31.42 ± 1.08 °C in the vastus lateralis and 31.55 ± 0.98 °C in the rectus femoris.

Figure 1 Representative thermographic images of the anterior thigh region obtained during early passive recovery after the incremental treadmill test (0–5 min shown). Images at 0–4 min are from the same athlete; the 5-min image is from a different athlete.



Rather than exhibiting a progressive cooling response, the thermal pattern suggests a transient stabilization of cutaneous temperature, likely reflecting the balance between post-exercise vasodilation, residual metabolic heat, and the gradual onset of thermoregulatory heat dissipation. This response aligns with evidence indicating that, immediately after exercise, local skin temperature may remain unchanged or slightly elevated before manifesting a cooling trend as recovery progresses.

Table 1 Skin temperature (°C) of vastus lateralis and rectus femoris during the first 6 minutes of passive recovery

Time (min)	Vastus lateralis	Rectus femoris
0 (Rest)	31.28 ± 1.04	31.01 ± 1.11
1	31.20 ± 1.19	31.63 ± 1.17
2	31.26 ± 1.16	31.38 ± 1.04
3	31.36 ± 1.16	31.44 ± 0.95
4	31.49 ± 1.22	31.62 ± 1.07
5	31.40 ± 1.06	31.52 ± 0.92
6	31.42 ± 1.08	31.55 ± 0.98

Note. Data are expressed as mean ± standard deviation (N = 20). Minute 0 corresponds to the measurement recorded immediately after test completion, with the participant seated at rest (i.e., the start of passive recovery).

Table 2 presents the absolute temperature change and thermal slope over time. The mean absolute temperature change between minute 0 and minute 6 was 1.53 ± 0.82 °C in the vastus lateralis and 1.24 ± 0.42 °C in the rectus femoris. The thermal slopes were 0.041 ± 0.158 °C·min^{-1} for the vastus lateralis and –0.005 ± 0.120 °C·min^{-1} for the rectus femoris, indicating an essentially flat temporal trend, with slopes close to zero. No marked regional differences were detected between muscles.

The correlation analysis (Table 3) revealed strong positive relationships among all thermographic variables. The associations between ΔT vastus femoralis and ΔT rectus femoralis (r = .848, p < .001), and between Slope T vastus femoralis and Slope T rectus femoralis (r = 0.809, p < .001), indicate a coordinated thermal response between both muscle regions. No significant correlations were found between thermal variables and physiological indicators such as VO_2peak or post-exercise lactate (3 min), ps > .05.

Linear regression models (Table 4) demonstrated that neither aerobic capacity (VO_2peak) nor blood lactate at 3 min were significant predictors of temperature change (ΔT) or thermal slope (Slope T) in either muscle (ps > .05

Table 2 Descriptive statistics of temperature change (ΔT) and thermal slope variables for vastus lateralis and rectus femoris

Variable	*M* ± *SD*	Minimum	Maximum
ΔT vastus lateralis (°C)	1.53 ± 0.82	0.35	2.74
ΔT rectus femoris (°C)	1.24 ± 0.42	0.30	2.10
Slope T vastus lateralis (°C·min^{-1})	0.041 ± 0.158	–0.320	0.280
Slope T rectus femoris(°C·min^{-1})	–0.005 ± 0.120	–0.250	0.210

Note. ΔT was calculated as the absolute temperature difference between minute 0 (immediately post-exercise) and minute 6.

Table 3 Pearson correlation coefficients among temperature change (ΔT) and thermal slope variables for vastus lateralis and rectus femoris

Variable	1	2	3
1. ΔT vastus lateralis	–		
2. ΔT rectus femoris	.848***	–	
3. Slope T vastus lateralis	.912***	.764***	–
4. Slope T rectus femoris	.756***	.873***	.809***

Note. *** p < .001.

Table 4 Multiple linear regression models predicting temperature change (ΔT) and thermal slope in vastus lateralis and rectus femoris

Variable/Predictor	β (*SE*)	*t*(19)	*p*	95% confidence interval	R^2
ΔT vastus lateralis					
VO_2peak (ml·min^{-1}·kg^{-1})	.018 (.074)	0.22	.823	[–0.14, 0.17]	.02
Lactate (3 min) (mmol·L^{-1})	–.115 (.190)	–0.61	.551	[–0.52, 0.28]	.03
ΔT rectus femoris					
VO_2peak (ml·min^{-1}·kg^{-1})	.010 (.060)	0.17	.872	[–0.12, 0.14]	.01
Lactate (3 min) (mmol·L^{-1})	–.148 (.100)	–1.47	.161	[–0.35, 0.06]	.04
Slope T vastus lateralis					
VO_2peak (ml·min^{-1}·kg^{-1})	–.015 (.010)	–0.98	.336	[–0.05, 0.02]	.02
Lactate (3 min) (mmol·L^{-1})	–.011 (.030)	–0.56	.584	[–0.09, 0.05]	.01
Slope T rectus femoris					
VO_2peak (ml·min^{-1}·kg^{-1})	.008 (.009)	0.75	.463	[–0.01, 0.03]	.01
Lactate (3 min) (mmol·L^{-1})	–.017 (.020)	–1.12	.275	[–0.06, 0.02]	.03

Note. β = standardized regression coefficient; *SE* = standard error.

for all models). The coefficients of determination were low (R^2 < .05), suggesting that these physiological factors explain only a small proportion of the variance in skin temperature dynamics. Overall, these findings indicate that post-exercise thermal recovery is primarily governed by local mechanisms of blood flow redistribution and heat transfer, rather than by systemic metabolic variables such as VO_2 or lactate accumulation.

Discussion

The present study investigated early post-exercise thermoregulatory behavior and lactate kinetics during passive recovery in trained volleyball players. The main findings were: (i) minimal changes in skin temperature (T_sk) of the quadriceps between 0 and 6 min after exercise; (ii) strong coherence between thermal responses of the vastus lateralis and rectus femoris; and (iii) absence of significant associations between T_sk slopes, blood lactate, or relative oxygen uptake (VO_2peak). Together, these results indicate that, during the first minutes of recovery, local autonomic–vascular adjustments prevail over metabolic or aerobic conditioning effects, resulting in a transient decoupling between surface thermography and systemic physiological markers.

Analysis of the data revealed minimal T_sk variations within the first 6 min of recovery, suggesting rapid cutaneous vasoconstriction and limited thermal exchange at the skin surface (James et al., 2025). This observation agrees with controlled studies showing that immediately after exercise termination, a reflex withdrawal of skin blood flow occurs to preserve central hemodynamics, particularly under passive recovery conditions (Greaney et al., 2021). In moderate to intense workloads, skin rewarming is delayed because of a transient mismatch between cardiac output redistribution and peripheral vascular tone (Chou & Coyle, 2023). Therefore, the small magnitude of T_sk reduction in our athletes likely reflects the dominance of autonomic cooling latency rather than the end of metabolic heat production.

This pattern contrasts with studies that employed longer observation windows or active cooling interventions, where greater T_sk drops are expected. For example, post-match cooling procedures in football players induced large anterior thigh temperature decreases of approximately 10–11 °C within minutes, accompanied by reductions in muscle enzyme activity over the following 24–48 hours (Corral-Pérez et al., 2023; Rojas-Valverde et al., 2021). In our passive context, however, the absence of forced convective cooling and the shorter time frame likely explain the limited ΔT observed between 0 and 6 min (Ahokas et al., 2025; Wellauer et al., 2025).

The absence of correlations between early T_sk dynamics and VO_2peak contrasts with reports where aerobic capacity predicted faster craniofacial or temporal cooling. Jastrzębska et al. (2022) observed significant correlations between temporal T_sk decay (the difference between temporal skin temperature 120 s after exercise and immediately after exercise) and VO_2max (r = .55) as well as maximal power output (r = .68) in healthy men (VO_2max = 59.0 ± 11.2 mL·kg^{-1}·min^{-1}). The discrepancy with our results may be due to both regional differences and temporal resolution: cranial regions exhibit higher perfusion and thinner subcutaneous layers, making them more responsive to core temperature shifts than the thigh musculature. Consequently, local thermography of large muscles might not capture the systemic aerobic recovery patterns that temporal regions reflect within the first two minutes (Jastrzębska et al., 2022).

Blood lactate measured at 3 min post-exercise was not associated with T_sk or cooling rates. This is consistent with the understanding that lactate clearance follows a delayed exponential decay, with its main phase occurring between 8 and 20 min post-exercise, depending on the recovery mode (Otani et al., 2021). Passive recovery, as applied in this study, limits active muscle perfusion and lactate oxidation, decoupling their kinetics from superficial thermal responses. Therefore, within the first minutes of recovery, metabolic markers (lactate) and cutaneous temperature appear to evolve independently.

Recent evidence highlights that the biophysical properties of underlying tissues substantially influence T_sk measurements. Amato et al. (2025) demonstrated that extracellular water (ECW) content strongly modulates thigh temperature profiles during and after exercise. In a cohort of 102 adults, both thighs showed an immediate post-exercise T_sk decrease (−0.52 °C and −0.63 °C for dominant and non-dominant legs, respectively; ps < .001) followed by a small rise at 5 min (+0.10–0.14 °C). Participants with higher water retention (ECW ≥ 45%) consistently exhibited lower T_sk values and even opposite trends during recovery, suggesting that water distribution and tissue conductivity directly affect heat dissipation rates (Amato et al., 2025). These results support our interpretation that interindividual variability in body composition, especially ECW and subcutaneous fat, may blunt the associations between metabolic performance and superficial temperature.

Complementarily, Carrión-González et al. (2025) investigated the relationship between T_sk and skin blood flow 24 hours after eccentric-induced muscle damage. Despite marked increases in creatine kinase and delayed onset muscle soreness, no significant rise in T_sk or skin blood flow was detected, and their correlation was only moderate (r = .59; Carrión-González et al., 2025). This finding reinforces that surface temperature cannot always serve as a proxy for deeper tissue processes such as inflammation or muscle perfusion. In line with our study, it emphasizes that T_sk changes primarily reflect vascular tone and environmental conductance, rather than biochemical recovery.

From a cardiovascular perspective, skin temperature recovery mirrors the dynamic balance between vasoconstriction to preserve blood pressure and vasodilation to dissipate residual heat. Greaney et al. (2021) described how, in young healthy adults, the threshold for cutaneous vasodilation occurs at smaller core–skin temperature gradients than in older individuals, implying that our sample of young athletes is physiologically predisposed to rapid

autonomic adjustments. Moreover, when the skin is warm, the cardiovascular system increases heart rate and reduces stroke volume to sustain cardiac output; yet, immediately after exercise cessation, these adaptations reverse to restore central perfusion (Chou & Coyle, 2023). This biphasic response aligns with the strong intermuscular coherence (r = .80–.85) observed in our athletes, indicating synchronized thermal recovery across the quadriceps while systemic variables normalize.

In applied settings, early post-exercise thermography (≤ 6 min) can provide valuable information on regional symmetry and local muscle behavior but should not be used as a sole indicator of systemic recovery. Combining infrared thermography with hemodynamic (laser-Doppler or NIRS) and metabolic (VO_2 off-kinetics, lactate clearance) assessments could capture the temporal interplay between local and systemic recovery processes. For practitioners, monitoring both T_sk coherence and cooling slopes may help identify localized fatigue or delayed vasomotor recovery, guiding individualized cooling or compression strategies.

The present study included only female volleyball players from a single professional team. Future research should consider (i) larger and more diverse samples, including men and older athletes; (ii) additional muscle regions such as hamstrings or trunk; (iii) extended post-exercise windows (≥ 15–20 min); and (iv) simultaneous recording of skin blood flow, muscle oxygenation (NIRS), and ECW. Such multimodal approaches would clarify the relative contributions of vascular, metabolic, and compositional factors to thermographic responses.

Several limitations should be acknowledged. First, menstrual cycle phase was not controlled or recorded. Fluctuations in estrogen and progesterone levels may influence thermoregulatory mechanisms, skin blood flow, and heat dissipation, potentially introducing intra-individual variability in thermal responses. Second, subcutaneous fat thickness and body composition variables directly affecting tissue thermal conductivity were not measured. Adipose tissue acts as a thermal insulator and may attenuate or delay cutaneous temperature changes, thereby influencing infrared thermography outcomes.

Third, the study included a relatively small sample of athletes from a single professional female volleyball team, which may limit generalizability. Additionally, only the anterior thigh region was assessed, and no direct measurements of skin blood flow or muscle oxygenation were obtained. Finally, the recovery protocol was limited to passive seated recovery during the first 6 min post-exercise. Different recovery modalities or longer monitoring windows might yield distinct thermographic patterns.

Conclusions

In conclusion, very-early passive recovery (0–6 min) following incremental treadmill exercise is characterized by stable quadriceps skin temperature, high inter-regional coherence, and absence of association with lactate or VO_2peak in trained volleyball athletes. These findings, supported by recent literature, indicate that initial cooling is driven mainly by autonomic vasomotor control rather than aerobic or metabolic control.

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Conflict of interest

The authors report no conflict of interest.

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