Journal of Thermal Biology 123 (2024) 103923

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Effect of different Volumes of exercise on skin temperature responses over the following 24 hours

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A R T I C L E I N F O

Keywords:
Muscle damage
Pain
Delayed onset muscle soreness
Recovery
Infrared thermography

A B S T R A C T

Skin temperature responses have been advocated to indicate exercise-induced muscle soreness and recovery status. While the evidence is contradictory, we hypothesize that the presence of muscle damage and the time window of measurement are confounding factors in the skin temperature response. The objective was to determine whether skin temperature is influenced by different workloads and the time course of temperature measurements over the following 24 h. 24 trained male military were assigned to one of three groups: GC group (n = 8) serving as control not performing exercises, GE group (n = 8) performing a simulated military combat protocol in an exercise track with different obstacles but designed not to elicit muscle damage, and the GEMD group (n = 8) performing the simulated military combat protocol plus 5 sets of 20 drop jumps, with 10-sec between repetitions and with 2-min of rest between sets aiming to induce muscle damage. Skin temperature was measured using infrared thermography before exercise (Pre) and 4 (Post4h), 8 (Post8h) and 24h (Post24h) post-exercise. Perception of pain (DOMS) was evaluated Pre, Post24h, and Post48h, and countermovement jump height was evaluated at Pre and Post24h. DOMS did not differ between groups in the Pre and Post24h measures but GEMD presented higher DOMS than the other groups at Post48h ($p < 0.001$ and large effect size). Jump height did not differ for GEMD and GC, and GE presented higher jump height at Post24h than GC ($p = 0.02$ and large effect size). Skin temperature responses of GEMD and GG were similar in all measurement moments ($p > 0.22$), and GE presented higher skin temperature than the GC and the GEMD groups at Post24h ($p < 0.01$ and large effect sizes). In conclusion, although physical exercise elicits higher skin temperature that lasts up to 24 h following the efforts, muscle soreness depresses this response.

1. Introduction

Exercise-induced muscle damage (EIMD) is a potential consequence of physical exercise, especially when it comes to rapid increases in training loads and movement profiles different from usual and/or after, with a predominance of eccentric muscle action (Brown et al., 1997; Douglas et al., 2017; Proske and Morgan, 2001). EIMD results in muscle inflammation, which could lead to delayed onset muscle soreness (DOMS) (Cheung et al., 2003). DOMS is associated with muscle tenderness, reduced range of motion, stiffness, and swelling (Lewis et al., 2012). Quantifying EIMD and DOMS is helpful for training planning and recovery assessment (Hotfiel et al., 2018; Mujika, 2017). Infrared thermography (IRT) could help to identify EIMD based on the idea that muscle inflammation increases the heat transferred to the skin (de Andrade Fernandes et al., 2017; Priego Quesada and Vardasca, 2017).

However, to date, IRT has presented only controversial results regarding the ability to detect temperature variation resulting from EIMD. No alterations of skin temperature (T_{sk}) were observed measured by IRT 48h after EIMD protocols in gastrocnemius or quadriceps (da Silva et al., 2018, 2021; Ferreira-Júnior et al., 2021) and 24h and 48h

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https://doi.org/10.1016/j.jtherbio.2024.103923
Received 22 December 2023; Received in revised form 24 June 2024; Accepted 9 July 2024
Available online 16 July 2024

after half-marathon and marathon competitions (Pérez-Guarner et al., 2019; Priego-Quesada et al., 2020). Furthermore, no correlations were observed between creatine kinase, pain, and T_{sk} 48 h after soccer matches (Carvalho et al., 2021) or during a 10-day taper period in sprinters (Korman et al., 2021). On the other hand, studies reported increases in T_{sk} the day after a soccer match (de Andrade Fernandes et al., 2017), after 10 km of running (Priego-Quesada et al., 2022), after maximal knee contractions on a dynamometer (Stewart et al., 2020), or during three days of a triathlon training camp (Priego-Quesada et al., 2019).

Two hypotheses have been proposed to explain the conflicting results. Firstly, it is posited that the relationship between internal load and T_{sk} responses follows an inverted U-shaped curve. Consequently, while exercises not inducing muscle damage or pain may elevate baseline T_{sk}, the onset of pain or muscle damage could trigger peripheral vasoconstriction, nullifying any noticeable changes in T_{sk} (Priego-Quesada et al., 2020, 2022). This hypothesis finds support in previous studies showing that exercises resulting in low levels of DOMS have been associated with increased T_{sk} the day after exercise (Priego-Quesada et al., 2019, 2022; Stewart et al., 2020). Secondly, another hypothesis proposes the existence of an optimal time frame for assessing T_{sk} responses using IRT. A peak in T_{sk} response was noted between 5 and 9 h after completing a 10 km run (Priego-Quesada et al., 2022). Therefore, while the effects of EIMD may not manifest within 24 h post-exercise, shorter assessment intervals could reveal detectable changes. We suggest that identifying a possible best time window for using IRT to detect T_{sk} responses to EIMD is critical in advancing its applicability for monitoring internal training loads. Although measuring in a time window before the 24-h post-exercise may pose challenges in specific contexts (e.g., regular schedule training), in others it may be feasible and of interest, such as clinical settings, training camps, and multi-day competitions.

Therefore, in this study, we determine whether T_{sk} response is influenced by different workloads and the time course of temperature measurements over the following 24 h. Considering the hypothesis of an inverted U relationship between internal load and T_{sk}, we hypothesize that exercise-induced muscle damage influences T_{sk} response during recovery. Furthermore, the timing of temperature measurements may be crucial for interpreting the results.

2. Material and methods

2.1. Participants

A sample size of 24 military-trained males (McKay et al., 2021) were recruited for the study. The required sample necessary to determine differences in the thermal response between groups (repeated measures ANOVA for 3 groups and 4 measurements), taking into account effect sizes for ANOVA of 0.8 (Cohen's f) considering the results of a previous study (Priego-Quesada et al., 2022), with a statistical power of 95% and an error of 5% was 21 participants (G*Power 3 software, University of Düsseldorf, Düsseldorf, Germany). Participants were randomly divided into three groups (Table 1): a control without exercise (GC, 8 participants), an exercise group with a protocol that was not intended to generate muscle damage (GE, 8 participants), and a group that included a protocol of muscle damage induction (GEMD, 8 participants). Participants were asked about their leg preference by asking, "If you would kick a ball aiming at a target, which leg would you prefer to kick?" (van Melick et al., 2017). Twenty participants reported right preference, while 4 reported left preference. All participants signed a consent form agreeing to participate, and all procedures established in the Helsinki Declaration were respected. The University's local ethics committee approved this research (IRB: 2626957).

Participants had no history of previous injuries. To avoid the possible effect of external factors, the participants were instructed to avoid, during the day of measurements and 6h before the first measurement, a different physical exercise as requested by the current study (and no exercise on the previous day), and refrain from anti-inflammatory substances, alcohol consumption, caffeinated drinks, cigarettes, hot baths, sunbathing, and use of creams and cosmetics (Moreira et al., 2017; Priego Quesada et al., 2017).

2.2. Experimental design

Data collection was conducted over three consecutive days. On day 1, the participants performed a 15-min room adaptation before the IRT measurements. After IRT measurements, values of DOMS and three countermovement jumps (CMJs) were recorded.

After baseline measurements, the GE completed a military combat simulation exercise (Fig. 2), and the GEMD completed a military combat simulation and an exercise protocol to induce damage by drop jumps. The CG did not perform any exercise. The participants returned 4h, 8h, and 24h after the exercise to perform IRT assessments again. The DOMS and CMJ assessments were repeated 24 h after the exercise. 48 h after the exercise, only the DOMS assessment was evaluated. Fig. 1 depicts our experimental design.

2.3. Military combat simulation exercise

The GE and the GEMD performed a standard military combat simulation exercise protocol wearing the assault equipment: standard combat uniform, boots, a weapon, chest-webbing body armor, helmet, and ammunition (approximately 20 kg up to the soldier's body mass). This protocol was structured on an exercise track with different obstacles (Table 2). The combat simulation was structured to submit the participant to strength and resistance stimuli for the whole body. All participants were instructed to perform the simulation at the highest possible speed. Before starting, all participants were reminded of how to perform the exercises, as they had previous experience in the simulation. The protocol was always performed in pairs and monitored by the same evaluator to ensure proper execution of the exercises. The mean duration of the combat protocol simulation was 6.4 ± 0.4 min.

2.4. Muscle damage protocol

After the combat simulation protocol, participants from GEMD completed a drop jump protocol to elicit EIMD in quadriceps muscles.

Table 1
Participants characteristics. All values are presented as mean ± SD.

Parameter	Control without exercise (GC; N = 8)	Exercise group (GE; N = 8)	Exercise muscle damage group (GEMD; N = 8)
Age (years)	48 ± 10	35 ± 5	35 ± 5
Body mass (kg)	76.9 ± 6.3	72.9 ± 10.4	80.4 ± 5.6
Height (cm)	173 ± 4	174 ± 10	178 ± 3
Body mass index (kg/m^2)	22.8 ± 9.6	23.8 ± 1.5	25.0 ± 1.4
Physical activity volume (h/week)	8 ± 3	6 ± 1	9 ± 4
Strength training volume (h/week)	3 ± 1	4 ± 1	5 ± 2

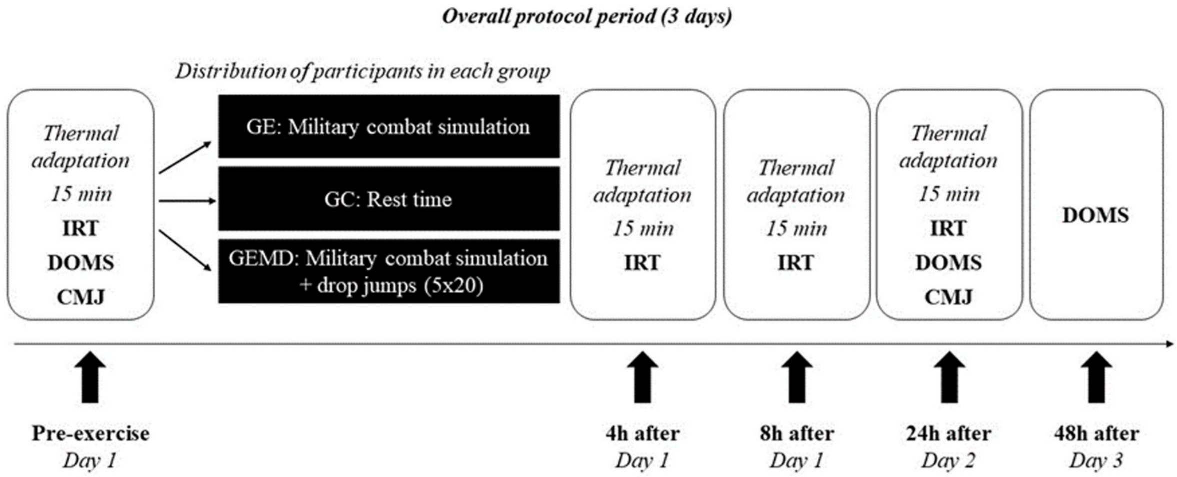

Fig. 1. Experimental design illustrating the different phases of the study comprising three days of testing of three experimental groups. GE: group exercise; GC: control group; GEMD: group exercise and muscle damage; IRT: infrared thermography, DOMS: delayed onset muscle soreness, and CMJ: countermovement jump, outcomes were evaluated in different time windows following exercise or rest intervention.

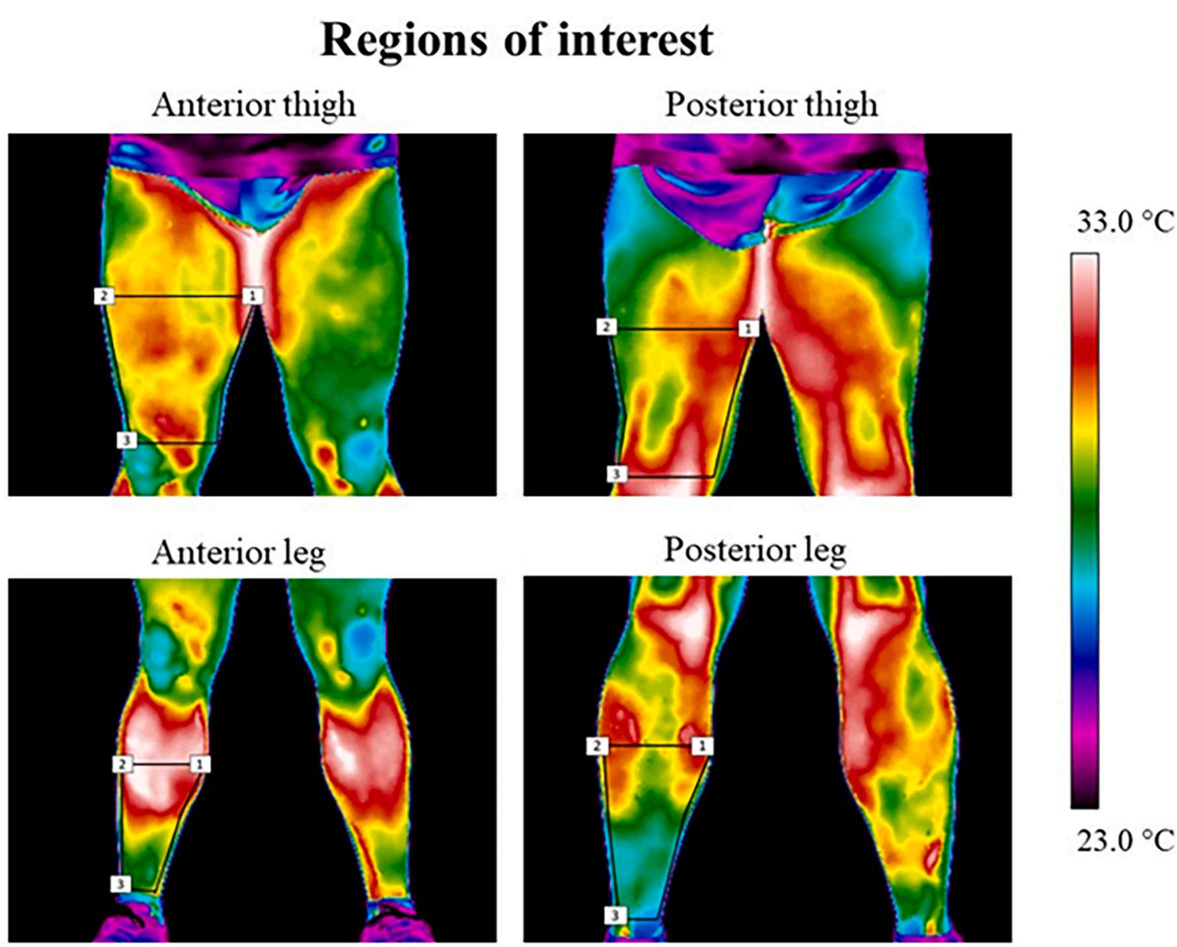

Fig. 2. The image is from one representative participant and shows the different regions of interest considered for skin temperature measures, in which temperature values are identified by the color table ranging from 23 to 33 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

All drop jumps were performed from the top of a 60 cm height box. Firstly, all participants receive instructions and a demonstration of the drop jump technique. The task consisted of an initial position standing with lower limbs straight, dropping from the top of the box to the ground level just in front of the participant, landing with a knee flexion of around 90°, jumping as high as possible, and finishing the task by landing again in the same place. This protocol was performed in 5 sets of 20 drop jumps, with 10 between repetitions and 2-min of rest between sets (Howatson et al., 2009).

Table 2
Exercises carried out in the military combat simulation.

Exercise	D (")/L (m)/H (m)
Shoveling sand	D 2 x 30" (right/left)
Crawling and pushing a 9 kg tire	L 30 m
Stair type obstacle course	L 2.5 m, H 2 m
Climbing up and down stairs with 2 ammunition boxes (12 kg each)	H 4 m
Vertical obstacle	H 2.5 m
Zig-zag	L 25 m
Vertical dry pit	H 4.5 m
Slope	L 20 m
Crawling wire fence	L 20 m
Throwing 5 grenades from ground knee position	D_{max} 20"
Moving through a trench	L 20 m
Climbing a wall	H 2 m
Airsoft pistol shooting (10 shoots)	D_{max} 30"

Note. $D_{(max)}$: Duration $_{(maximum)}$, L: Length, H: Height. After each exercise, the participants had to fall down, assuming a prone firing position. The total course was approximately 290 m.

2.5. *Skin temperature measurement*

The T_{sk} was measured using a thermographic camera (E54 model, 320 x 240 pixels resolution, NETD <40 mK at 30°, and measurement uncertainty of ±2 °C or 2%, Flir Systems Inc., Wilsonville, USA). Before all measures, the camera was turned on for 10 min, and participants completed a thermal room adaptation of 15 min (Marins et al., 2014). During this period, the participants were instructed to rest in an orthostatic position with lower limbs exposed, moving as little as possible and not touching the regions of interest (ROIs). All thermal images were taken 1 m from the participant, with the camera lens positioned perpendicular to the ROIs by the same evaluator.

The ROIs were defined based on anatomical criteria established in a previous study (Da Silva et al., 2022). Four ROIs were defined (Fig. 2) in the anterior thighs (right and left) and posterior legs (right and left). The ThermaCAM Researcher Pro software (version 2.10, FLIR, Wilsonville, USA) was used to obtain the mean T_{sk} from each ROI. The temperature variation for each moment was defined as the difference between the baseline and the first day (ΔT_{sk}) of measurement. All measurements were performed at a temperature controlled by air conditioning. The mean (standard deviation) of the environmental conditions for day 1 was: room temperature 21.8 ± 0.5 °C and humidity 41.7 ± 2.0%, and for day 2 was: room temperature 21.5 ± 0.5 °C and humidity 41.4 ± 1.0%. All procedures followed the Thermographic Imaging in Sports and Exercise Medicine checklist (Moreira et al., 2017).

2.6. *Muscle soreness assessment*

EIMD was quantified indirectly by the presence of DOMS evaluated by a numeric pain rating scale (NPRS) from 0 (no pain) to 10 (extreme pain) (Hawker et al., 2011). The values of NPRS were explained to the participants. They were instructed to report the intensity of pain sensation in both anterior thighs (left and right) while performing a single squat. The same evaluator always performed the evaluation. On day 3, the NPRS was evaluated remotely.

2.7. *Countermovement jumps*

Jump height was measured for each CMJ using the Chronojump platform (model DIN-A3; Chronojump-Boscosystem, Barcelona, Spain). Before data collection, participants performed a warm-up consisting of 15–20 squat exercise repetitions and joint mobility (Priego-Quesada et al., 2020). From the upright posture with the hands placed at the hips, they performed a quick semi-squat movement reaching 90° of knee flexion, and a fastest possible upward movement to jump as high as possible and land on their toes. They performed three repetitions of the countermovement jump, with a 30-s rest interval in between (Guglielmo et al., 2009). The mean of the three jumps was calculated, and the jump variation (% of the difference between the Post24h and Pre-exercise measures) was used for data analysis.

2.8. *Statistical analysis*

Statistical analyses were performed using RStudio (version 2022.02.03) and an alpha set at 0.05. Data are reported with mean, standard deviation, 95% confidence interval (95%CI) for parametric data, and median and interquartile range (IQR) for non-parametric data. The normality of data distribution was checked for each variable with the Shapiro-Wilk test. DOMS presented a non-parametric distribution; then the Wilcoxon test was performed to check if there were differences between the preferred and the non-preferred anterior thigh, followed by a Kruskal Wallis test with Mann-Whitney U post-hocs to evaluate the differences between groups for each moment. For jump variation, an ANOVA with Bonferroni post-hoc was performed to assess the differences between groups, with this analysis performed using the "ggstatsplot" package (Patil, 2021). For c, ANOVA repeated measures with Bonferroni post-hocs were applied for each ROI with two intra-subject factors (measurement moment and leg preference) and one inter-subject factor (group). For significant pair differences, Hedge's effect sizes (ESg) were computed with paired correction using the package "effectsize" and classified as small (ESg 0.2–0.5), moderate (Esg 0.5–0.8), or large (ESg>0.8) (Cohen, 1988; Hedges, 1981). Finally, an exploratory analysis was performed to assess the relationship between ΔT_{sk} at Post24h in the anterior thigh and DOMS in the anterior thigh at Post24h and Post48h, using linear regression and quadratic regression (for verifying the hypothetical U-inverted relationship).

3. Results

No differences (p = 0.57) in DOMS were observed between both anterior thighs (preferred vs. non-preferred); therefore, this factor was not considered in the following analysis. DOMS did not differ between groups in the Pre (p-value not obtained for low variability, 0.0 - IQR 0.0 points for the three groups) and Post24h measures (p = 0.07, GC 0.0 - IQR 0.0 points vs. GE 0.5 - IQR 1.3 points vs. GEMD 0.0 - IQR 0.3 points). However, in the Post48h measure, GEMD reported higher DOMS than the other groups (Kruskal Wallis p < 0.001, GC 0.0 - IQR 0.3 points vs. GE 0.0 - IQR 1.0 points vs. GEMD 3.5 - IQR 3.8 points; GC vs. GE p =

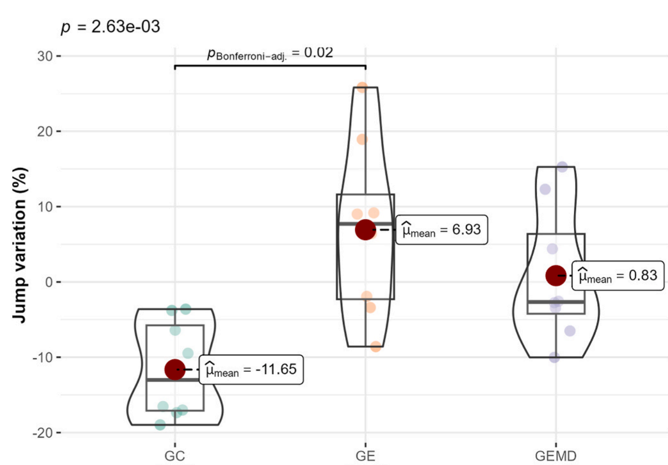

Fig. 3. Violin plot of the jump variation (% difference between the post-24 h and the pre-exercise measures) for the three groups assessed (GC: control group; GE: group exercise; GEMD: group exercise and muscle damage).

0.18, GC vs. GEMD $p < 0.001$ and ESg = 1.7, GE vs. GEMD $p < 0.001$ and ESg = 1.4).

At Post24h, jump variation did not differ between GEMD and GC ($p = 0.09$, Fig. 3) and GE ($p = 0.31$), but GE participants showed larger jump variation than the GC group (95%CI of the difference [6.4, 30.7%] and ESg = 1.9).

Because the statistical analyses considered ΔT_{sk}, the values at pre measure describe the starting point of each group: preferred anterior thigh 29.7 ± 0.9 °C, non-preferred anterior thigh 29.8 ± 0.9 °C, preferred anterior leg 30.5 ± 0.8 °C, non-preferred anterior leg 30.6 ± 0.8 °C, preferred posterior thigh 30.2 ± 0.9 °C, non-preferred posterior thigh 30.3 ± 0.9 °C, preferred posterior leg 30.5 ± 0.7 °C, and non-preferred posterior leg 30.3 ± 0.8 °C. The main effect of leg preference was not significant in the variation of baseline mean T_{sk} ANOVAs ($p > 0.79$), nor was its interaction with the other factors ($p > 0.90$). Therefore, leg preference was not considered a factor in the following results.

Fig. 4 shows the evolution of baseline T_{sk}. GEMD did not differ from the GC group at any measurement window ($p > 0.22$). At Post4h, GE presented higher T_{sk} than GC for all the ROIs (e.g., anterior thigh 95%CI [0.5, 1.7 °C], $p < 0.01$ and ESg = 1.4), and in the case of the anterior thigh, GE was also different to GEMD (95%CI[0.3, 1.3 °C], $p < 0.01$ and ESg = 1.4). At Post24h, GE presented also higher T_{sk} than the GC (e.g., anterior thigh 95%CI[0.9, 1.5 °C], $p < 0.001$ and ESg = 2.6) and the GEMD (e.g., anterior thigh 95%CI[0.6, 1.6 °C], $p < 0.01$ and ESg = 1.6).

Regarding the pre-measurement, in general, the three groups increased temperature at the Post4h measure (GC: e.g., anterior leg 95% CI[0.2, 0.8 °C], $p = 0.02$ and ESg = 1.2; GE: e.g., anterior thigh 95%CI [1.3, 2.0 °C], $p < 0.001$ and ESg = 4.0; GEMD: e.g., anterior thigh 95%CI [0.6, 1.1 °C], $p < 0.001$ and ESg = 2.3), with less intensity at the Post8h measure (GC: posterior thigh 95%CI[0.2, 0.8 °C], $p = 0.03$ and ESg = 1.1; GE: e.g., anterior thigh 95%CI[0.7, 1.3 °C], $p < 0.001$ and ESg = 2.5; GEMD: e.g., anterior thigh 95%CI[0.7, 1.3 °C], $p < 0.001$ and ESg = 2.3).

However, the GE was the only group with higher T_{sk} at Post24h compared with the Pre measurement (e.g., anterior thigh 95%CI[0.9, 1.3 °C], $p < 0.001$ and ESg = 3.9).

The exploratory regression analysis showed no association between ΔT_{sk} at Post24h in the anterior thigh and DOMS in the anterior thigh at Post24h (Fig. 5A) for linear ($p = 0.55$) and quadratic regressions ($p = 0.54$). No associations were observed between ΔT_{sk} at Post24h in the anterior thigh and DOMS in the anterior thigh at Post48h (Fig. 5B).

4. Discussion

Here, we determine whether T_{sk} response is influenced by different workloads and the time course of temperature measurements over the following 24 h. We hypothesize that the presence of muscle damage and the moment of measurement are confounding factors in the T_{sk} response. Our main findings revealed that exercise increased T_{sk} in lower limbs at Post24h compared to pre-exercise, and measures later than 24 h after exercise may not capture the acute adaptations that exercise can cause to T_{sk}. Such time influence may also influence data interpretation and comparisons between studies. However, the additional exercise load to elicit muscle damage depresses this response. Furthermore, including additional exercise load to elicit muscle damage leads to similar responses as observed in the control non-exercised group. These novel results show that muscle damage is a confounding factor in the theoretical association between physical exercise and T_{sk} responses. Furthermore, the T_{sk} measured 24h after the physical effort is a late measure, missing the complete kinetics of T_{sk} over the short-term recovery.

We considered a novel approach to the exercise intervention; therefore, understanding the different groups' context is crucial for

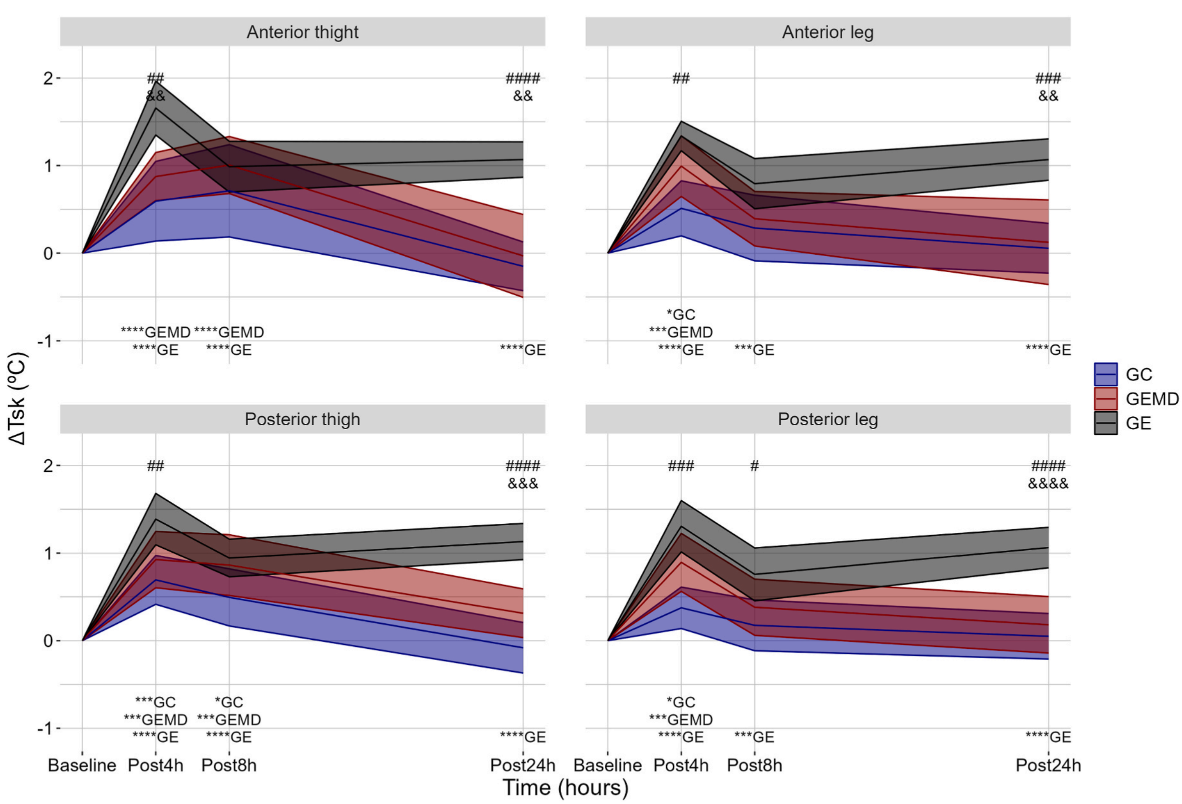

Fig. 4. Mean and 95%CI of the variation of baseline skin temperature (ΔT_{sk}) for the groups GC: control group; GEMD: group exercise and muscle damage; GE: group exercise. No differences were observed between GC and GEMD at any moment. Different symbols were used: differences between GC and GE (#p < 0.05, ##p < 0.01, ###p < 0.001, ####p < 0.0001), differences between GE and GEMD (& p < 0.05, && p < 0.01, &&&p < 0.001, &&&&p < 0.001) and differences of each group with the baseline (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.001).

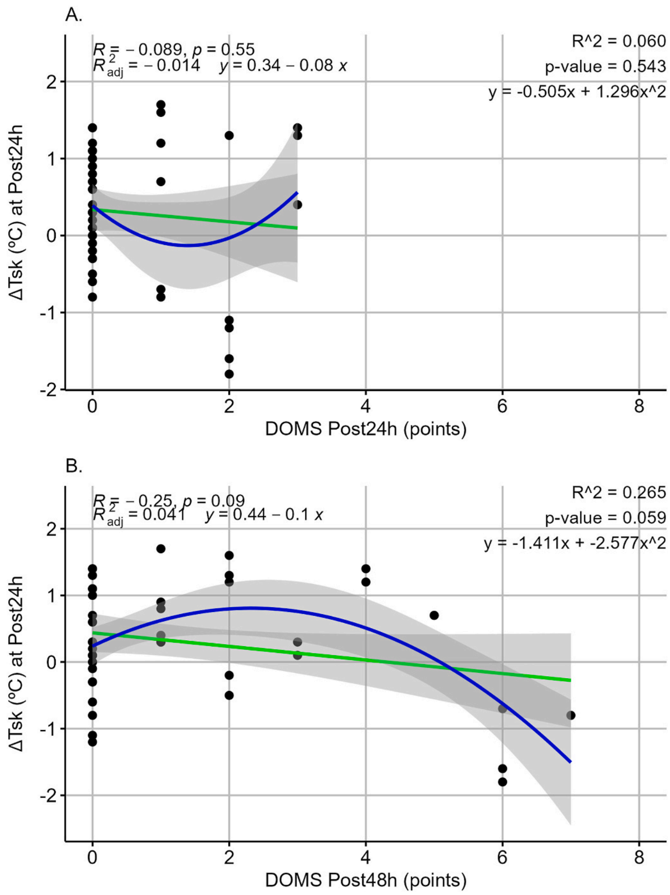

Fig. 5. Relationship between skin temperature variation (ΔT_{sk}) at Post24h in the anterior thigh and DOMS in the anterior thigh at Post24h (A) and Post48h (B), using linear regression (green line, results showed in the upper left side of the graphs) and quadratic regression (blue line, results showed in the upper right side of the graphs). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

interpreting our results. Firstly, previous studies considering the same muscle damage protocol obtained DOMS values of 3–4 out of 10 points on 24 and 48h post-exercise (Cardoso et al., 2020; Dias et al., 2022; Ghoth et al., 2019). Here, the GEMD group showed a similar increase in DOMS at Post48h (3.5 points) but not at Post24h. We considered a specialized sample of military males who are used to consecutive days of intense effort, which can explain the lack of DOMS at Post24h. Moreover, the lack of a significant increase in DOMS at Post24h may explain the preserved jump performance that we found in GEMD participants. We consider this evidence as providing reasonable support for the idea that the different T_{sk} responses observed between the GE and GEMD groups are due more to the EIMD (due to their differences in the workload performed) than to the DOMS (which was no different between groups at Post24h)

The literature presents conflicting results regarding the kinetics of T_{sk} 24 and 48 h after exercise (da Silva et al., 2021; de Andrade Fernandes et al., 2017; Priego-Quesada et al., 2020; Stewart et al., 2020). An explanation could be based on a curvilinear inverted U relationship between internal load and T_{sk} responses (Priego-Quesada et al., 2020, 2022). We hypothesized that the GE would increase their T_{sk} during the day more than the other two groups. Our results support this hypothesis, as the GE group increased at Post24h their T_{sk} in lower limbs concerning pre-exercise, with higher T_{sk} than the other two groups (GC and GEMD had the same T_{sk} at Post24h than at Pre). Although these findings align with the proposed inverted U relationship, further investigations are needed to elucidate the physiological mechanisms driving T_{sk} behavior.

It is suggested that peripheral vasoconstriction may explain the lack of an increase in T_{sk} (Priego-Quesada et al., 2020) when muscle damage or pain occurs. Firstly, future studies should consider analyzing blood perfusion with other external and internal load parameters (e.g., biochemical parameters) related to metabolism and muscle tissue damage to validate the inverted U relationship between training load and T_{sk} response. Secondly, our results may help explain that this vasoconstriction is mainly due to muscle damage and not pain perception. Our exploratory regression analysis confirms that no significant relationships were obtained between DOMS and T_{sk}. Future studies should explore potential relationships between ΔT_{sk} at 24 h post-exercise and associated DOMS at 48 h post-exercise in a broader range of participants and exercise backgrounds.

We also highlight that our results may have important implications for the assessment routine. Infrared thermography in sports clubs often relies on pre-training measurements, with T_{sk} typically measured 24 or 48 h after physical exercise (Carvalho et al., 2021; de Andrade Fernandes et al., 2017; Korman et al., 2021). This routine may elicit a drawback if the T_{sk} responses occur in a shorter interval. We found peak T_{sk} 4 h after exercise. The peak increase in temperature at the 4-h mark could be associated with the circadian cycle, but a thermoregulatory response cannot be ruled out. This response, following exercise, could cause overheating of the skin in the subsequent minutes/hours to restore the metabolic and thermal equilibrium (Korman et al., 2024). Additionally, it could be influenced by the circadian cycle since even the control group (GC) exhibited increased T_{sk} at this time, though less intense than the GE group. These results partially align with a study on 10 km running, suggesting a temperature peak between 5 and 9 h post-exercise (Priego-Quesada et al., 2022). Discrepancies between studies may arise from differences in exercise type and measurement times. On the other hand, a baseline increase in T_{sk} may not necessarily indicate muscle damage but could be a natural response to non-damaging training. Conversely, a lack of T_{sk} increase from 4 to 24 h after high-load training may indicate muscle damage, which agrees with a previous study that showed how increasing creatine kinase during a 10d taper period in sprinters was accompanied by a T_{sk} decrease (Korman et al., 2021). However, it is crucial to remember the multifactorial dependence of T_{sk} and how other factors can also influence its response (environmental conditions, caffeine, etc.) (Fernández-Cuevas et al., 2015).

The study's main limitation was the lack of assessment of other parameters that helped interpret the results (e.g., core and muscle temperature, skin blood flow, creatine kinase, etc.). Another limitation was that due to the relatively small sample size, we only measured male participants, which did not allow us to study the effect of sex on the results. Finally, measuring physiological parameters 48 h after exercise would be desirable. However, it was not possible to alter the routine work of the military one more day than what had already been done.

5. Conclusion

Physical exercise leads to increases in T_{sk} that last up to 24 h following the effort. The presence of muscle soreness following exercise depresses T_{sk} response. The T_{sk} measured 24h after the physical effort seems to be a late measure, missing the kinetics of T_{sk} over the short-term recovery. Understanding how different time windows for measurement influence T_{sk} outcomes is crucial when designing experiments to explore potential connections between physical exercise and T_{sk} responses. Additionally, it is vital for accurately interpreting T_{sk} data. These results demonstrate the difficulty of associating the T_{sk} responses 24 h after exercise to the training load of the previous day or muscle damage processes.

Data accessibility statement

The dataset generated and analysed during the current study is available in the Mendeley repository (doi: 10.17632/gb6nzcmk4j.1).

Funding

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001 granted to WS and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) granted WS and ASM (401056/2022-8), and FC (301048/2019)

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Brown, S.J., Child, R.B., Day, S.H., Donnelly, A.E., 1997. Exercise-induced skeletal muscle damage and adaptation following repeated bouts of eccentric muscle contractions. J. Sports Sci. 15 (2), 2 https://doi.org/10.1080/026404197367498.

Cardoso, R., Lumini-Oliveira, J.A., Santos, M.J., Ramos, B., Matos, L.C., Machado, J., Greten, H.J., Franconi, G., 2020. Acupuncture can be beneficial for exercise-induced muscle soreness: a randomised controlled trial. J. Bodyw. Mov. Ther. 24 (1), 8–14. https://doi.org/10.1016/j.jbmt.2019.03.015.

Carvalho, G. de, Girasol, C.E., Gonçalves, L.G.C., Guirro, E.C.O., Guirro, R.R. de J., 2021. Correlation between skin temperature in the lower limbs and biochemical marker, performance data, and clinical recovery scales. PLoS One 16 (3), e0248653. https://doi.org/10.1371/journal.pone.0248653.

Cheung, K., Hume, P.A., Maxwell, L., 2003. Delayed onset muscle soreness: Treatment Strategies and performance factors. Sports Med. 33 (2), 145–164. https://doi.org/10.2165/00007256-200333020-00005.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences, second ed. Routledge.

Da Silva, W., Machado, Á.S., Kunzler, M.R., Jimenez-Perez, I., Gil-Calvo, M., Priego-Quesada, J.I., Carpes, F.P., 2022. Reproducibility of skin temperature analyses by novice and experienced evaluators using infrared thermography. J. Therm. Biol. 110, 103345 https://doi.org/10.1016/j.jtherbio.2022.103345.

da Silva, W., Machado, Á.S., Lemos, A.L., de Andrade, C.F., Priego-Quesada, J.I., Carpes, F.P., 2021. Relationship between exercise-induced muscle soreness, pain thresholds, and skin temperature in men and women. J. Therm. Biol. 100, 103051 https://doi.org/10.1016/j.jtherbio.2021.103051.

da Silva, W., Machado, Á.S., Souza, M.A., Kunzler, M.R., Priego-Quesada, J.I., Carpes, F. P., 2018. Can exercise-induced muscle damage be related to changes in skin temperature? Physiol. Meas. 39 (10), 10 https://doi.org/10.1088/1361-6579/aae6df.

de Andrade Fernandes, A., Pimenta, E.M., Moreira, D.G., Sillero-Quintana, M., Marins, J. C.B., Morandi, R.F., Kanope, T., Garcia, E.S., 2017. Skin temperature changes of under-20 soccer players after two consecutive matches. Sport Sci. Health 13 (3), 3. https://doi.org/10.1007/s11332-017-0394-1.

Dias, S.S., Weber, M.G., Padoin, S., Andrello, A.C., Jussiani, E.I., de Paula Ramos, S., 2022. Circulating Concentration of Chemical Elements during exercise-induced muscle damage and the repeated bout effect. Biol. Trace Elem. Res. 200 (3), 1060–1070. https://doi.org/10.1007/s12011-021-02737-8.

Douglas, J., Pearson, S., Ross, A., McGuigan, M., 2017. Eccentric exercise: physiological Characteristics and acute responses. Sports Med. 47 (4), 4 https://doi.org/10.1007/s40279-016-0624-8.

Fernández-Cuevas, I., Bouzas Marins, J.C., Arnáiz Lastras, J., Gómez Carmona, P.M., Piñonosa Cano, S., García-Concepción, M.Á., Sillero-Quintana, M., 2015. Classification of factors influencing the use of infrared thermography in humans: a review. Infrared Phys. Technol. 71, 28–55. https://doi.org/10.1016/j.infrared.2015.02.007.

Ferreira-Júnior, J.B., Chaves, S.F.N., Pinheiro, M.H.A., Rezende, V.H.S., Freitas, E.D.S., Marins, J.C.B., Bara-Filho, M.G., Vieira, A., Bottaro, M., Costa, C.M.A., 2021. Is skin temperature associated with muscle recovery status following a single bout of leg press? Physiol. Meas. 42 (3), 034002 https://doi.org/10.1088/1361-6579/abe9fe.

Ghoth, M.H.M., Amir, N.H., Radzi, J.A., Aznan, E.A.M., Japilus, S.J.M., Ramle, M.Y.M., 2019. Comparison between two recovery methods: cold water immersion versus progressive muscle relaxation in reducing DOMS among young athletes. Malaysian Journal of Movement, Health & Exercise 8 (2), 67.

Guglielmo, L.G.A., Greco, C.C., Denadai, B.S., 2009. Effects of strength training on running Economy. Int. J. Sports Med. 30 (1), 27–32. https://doi.org/10.1055/s-2008-1038792.

Hawker, G.A., Mian, S., Kendzerska, T., French, M., 2011. Measures of adult pain: Visual analog scale for pain (VAS pain), numeric rating scale for pain (NRS pain), McGill pain Questionnaire (MPQ), short-form McGill pain Questionnaire (SF-MPQ), Chronic pain Grade scale (CPGS), short form-36 Bodily pain scale (SF-36 BPS), and measure of Intermittent and Constant Osteoarthritis pain (ICOAP). Arthritis Care Res. 63 (Suppl. 11), S240–S252. https://doi.org/10.1002/acr.20543.

Hedges, L.V., 1981. Distribution theory for Glass's Estimator of effect size and related Estimators. J. Educ. Stat. 6 (2), 107–128. https://doi.org/10.2307/1164588.

Hotfiel, T., Freiwald, J., Hoppe, M.W., Lutter, C., Forst, R., Grim, C., Bloch, W., Hüttel, M., Heiss, R., 2018. Advances in delayed-onset muscle soreness (DOMS): Part I: Pathogenesis and Diagnostics. Sportverletz Sportschaden 32 (4), 243–250. https://doi.org/10.1055/a-0753-1884.

Howatson, G., Goodall, S., van Someren, K.A., 2009. The influence of cold water immersions on adaptation following a single bout of damaging exercise. Eur. J. Appl. Physiol. 105 (4), 615–621. https://doi.org/10.1007/s00421-008-0941-1.

Korman, P., Kusy, K., Kantanista, A., Straburzyńska-Lupa, A., Zieliński, J., 2021. Temperature and creatine kinase changes during a 10d taper period in sprinters. Physiol. Meas. 42 (12), 124001 https://doi.org/10.1088/1361-6579/ac3d76.

Korman, P., Kusy, K., Straburzyńska-Lupa, A., Kantanista, A., Quintana, M.S., Zieliński, J., 2024. Response of skin temperature, blood ammonia and lactate during incremental exercise until exhaustion in elite athletes. Sci. Rep. 14 (1), 2237. https://doi.org/10.1038/s41598-024-52374-z.

Lewis, P.B., Ruby, D., Bush-Joseph, C.A., 2012. Muscle soreness and delayed-onset muscle soreness. Clin. Sports Med. 31 (2), 255–262. https://doi.org/10.1016/j.csm.2011.09.009.

Marins, J.C.B., Moreira, D.G., Cano, S.P., Quintana, M.S., Soares, D.D., Fernandes, A. de A., Silva, F. S. da, Costa, C.M.A., Amorim, P.R. dos S., 2014. Time required to stabilize thermographic images at rest. Infrared Phys. Technol. 65, 30–35. https://doi.org/10.1016/j.infrared.2014.02.008.

McKay, A.K.A., Stellingwerff, T., Smith, E.S., Martin, D.T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J., Burke, L.M., 2021. Defining training and performance Caliber: a participant Classification Framework. Int. J. Sports Physiol. Perform. 17 (2), 317–331. https://doi.org/10.1123/ijspp.2021-0451.

Moreira, D.G., Costello, J.T., Brito, C.J., Adamczyk, J.G., Ammer, K., Bach, A.J.E., Costa, C.M.A., Eglin, C., Fernandes, A.A., Fernández-Cuevas, I., Ferreira, J.J.A., Formenti, D., Fournet, D., Havenith, G., Howell, K., Jung, A., Kenny, G.P., Kolosovas-Machuca, E.S., Maley, M.J., et al., 2017. Thermographic imaging in sports and exercise medicine: a Delphi study and consensus statement on the measurement of human skin temperature. J. Therm. Biol. 69, 155–162. https://doi.org/10.1016/j.jtherbio.2017.07.006.

Mujika, I., 2017. Quantification of training and competition loads in Endurance sports: methods and applications. Int. J. Sports Physiol. Perform. 12 (s2) https://doi.org/10.1123/ijspp.2016-0403. S2-9-S2-17.

Patil, I., 2021. Visualizations with statistical details: the 'ggstatsplot' approach. J. Open Source Softw. 6 (61), 3167. https://doi.org/10.21105/joss.03167.

Pérez-Guarner, A., Priego-Quesada, J.I., Oficial-Casado, F., Cibrián Ortiz de Anda, R.M., Carpes, F.P., Palmer, R.S., 2019. Association between physiological stress and skin temperature response after a half marathon. Physiol. Meas. 40 (3), 34009–34019. https://doi.org/10.1088/1361-6579/ab0fdc.

Priego Quesada, J.I., Kunzler, M.R., Carpes, F.P., 2017. Methodological Aspects of infrared thermography in human assessment. In: Application of Infrared Thermography in Sports Science. Springer International Publishing, pp. 49–79. http://link.springer.com/chapter/10.1007/978-3-319-47410-6_3.

Priego Quesada, J.I., Vardasca, R., 2017. Issues and future Developments of infrared thermography in sports Science. In: Application of Infrared Thermography in Sports Science. Springer International Publishing, pp. 297–319. http://link.springer.com/chapter/10.1007/978-3-319-47410-6_12.

Priego-Quesada, J.I., Catalá-Vilaplana, I., Bermejo-Ruiz, J.L., Gandia-Soriano, A., Pellicer-Chenoll, M.T., Encarnación-Martínez, A., Cibrián Ortiz de Anda, R., Salvador-Palmer, R., 2022. Effect of 10 km run on lower limb skin temperature and thermal response after a cold-stress test over the following 24 h. J. Therm. Biol. 105, 103225 https://doi.org/10.1016/j.jtherbio.2022.103225.

Priego-Quesada, J.I., Oficial-Casado, F., Gandia-Soriano, A., Carpes, F.P., 2019. A preliminary investigation about the observation of regional skin temperatures following cumulative training loads in triathletes during training camp. J. Therm. Biol. 84, 431–438. https://doi.org/10.1016/j.jtherbio.2019.07.035.

Priego-Quesada, J.I., Pérez-Guarner, A., Gandia-Soriano, A., Oficial-Casado, F., Galindo, C., Cibrián Ortiz de Anda, R.M., Piñeiro-Ramos, J.D., Sánchez-Illana, Á., Kuligowski, J., Gomes Barbosa, M.A., Vento, M., Salvador Palmer, R., 2020. Effect of a marathon on skin temperature response after a cold-stress test and its relationship with Perceptive, performance, and Oxidative-stress Biomarkers. Int. J. Sports Physiol. Perform. 15 (10), 10 https://doi.org/10.1123/ijspp.2019-0963.

Proske, U., Morgan, D.L., 2001. Muscle damage from eccentric exercise: Mechanism, mechanical signs, adaptation and clinical applications. J. Physiol. 537 (Pt 2), 2 https://doi.org/10.1111/j.1469-7793.2001.00333.x.

Stewart, I.B., Moghadam, P., Borg, D.N., Kung, T., Sikka, P., Minett, G.M., 2020. Thermal infrared imaging can Differentiate skin temperature changes associated with intense single leg exercise, but not with delayed onset of muscle soreness. J. Sports Sci. Med. 19 (3), 3.

van Melick, N., Meddeler, B.M., Hoogeboom, T.J., Nijhuis-van der Sanden, M.W.G., van Cingel, R.E.H., 2017. How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults. PLoS One 12 (12). https://doi.org/10.1371/journal.pone.0189876.