



A preliminary investigation about the observation of regional skin temperatures following cumulative training loads in triathletes during training camp

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ABSTRACT

There are controversial results in the literature concerning the concept that cumulative training load could affect basal skin temperature in the days following training sessions. The objective was to measure skin temperature in triathletes during a training camp with cumulative training load. Ten male recreational triathletes involved in a training camp underwent measurements of perception of pain and fatigue (visual analogue scale), skin temperature (infrared thermography), and jump performance (counter movement jump test) before, one day, and two days after the beginning of the training camp. All measurements were performed before the breakfast. Jump height did not differ between the days ($p > 0.05$). Fatigue perception increased after the first and second day of training for most of the body regions ($p < 0.05$). Pain perception increased after two days of training ($p < 0.05$). Mean and maximum skin temperature increased after the second day of training for most of the body regions ($p < 0.05$). Skin temperature in some body regions was directly related with muscle mass, weekly training volume, and inverse related with fatigue perception ($p < 0.05$ and $R^2 > 0.4$). Possible explanations of these results in comparison with previous studies may include the influence of control of the intrinsic and extrinsic factors related to the skin temperature assessment (for instance, the time of the day, lack of muscle soreness, daily activity control). These preliminary results have important implication on the use of skin basal temperature data to monitor exercise recovery, which claims for further research.

1. Introduction

Changes in skin temperature are mainly a result of perspiration, core temperature and environmental temperature, except by a contact of the body with other surface or exposition to convection streams (Ammer and Formenti, 2016). Skin temperature can also change in response to pathological processes such as inflammation, fever, vascular alterations or neurodegeneration (Hildebrandt et al., 2010; Lahiri et al., 2012; Ring and Ammer, 2012). Changes in skin temperature have been discussed as sensitive to physical exercise, especially concerning the recovery phase. Such relationship is still controversial in the literature and difficult to find support by the scientific literature. A higher activity of muscle metaboreceptors could increase sweating, but not skin blood flow (Amano et al., 2016; Paull et al., 2015). On the other hand, although it was found that muscle pain increases skin blood flow

(Lei et al., 2008), it was also observed a high variability between different populations (Burton et al., 2016). In addition, it was suggested a close coupling between skin blood flow, blood temperature, and increases of intravascular ATP (González-Alonso et al., 2015). Finally, despite the fact that skin blood flow could not be altered in the days after exercise, a higher muscle temperature could be transferred to the skin via conduction (Cramer and Jay, 2016).

Cumulative training load resultant of consecutive days of activity was shown to influence skin temperature (de Andrade Fernandes et al., 2017; Fernández-Cuevas et al., 2014), which was discussed as a result of the effect of exercise intensity on blood flow (Chevront et al., 2010; Schlager et al., 2010; Stöcker et al., 2018). However, there is no consensus in the results observed by the recent studies addressing the effects of physical exercise on skin temperature (de Andrade Fernandes et al., 2017; Pérez-Guarner et al., 2019; Silva et al., 2018). De Andrade

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Abbreviations

ΔT₂₄ skin temperature difference between measurement 24 h after the first day of training and the measurement before start the training
ΔT₄₈ skin temperature difference between measurement the day after two consecutive days of training and the measurement before start the training
Δknee_fatigue₄₈ fatigue perception difference at muscles spanning knee between measurement performed the day after two

consecutive days of training and the measurement before start the training
CMJ counter movement jump test
ES effects size.
ROI region of interest
Test_{pre} test before start the training
Test₁ test the day after start the first day of training
Test₂ test the day after two consecutive days of training
VAS Visual analogue scale

Fernandes et al. (de Andrade Fernandes et al., 2017) observed a progressive increase in lower limbs skin temperature after two consecutive soccer matches. However, such observation was not found during the evaluation of skin temperature following 48 h of strenuous calf raise exercise to induce muscle soreness (Silva et al., 2018), and 24 and 48 h after a half marathon performance (Pérez-Guarner et al., 2019). Despite of an increase in muscle soreness and creatine kinase activity, skin temperature remained stable in these studies. The divergence between studies with similar goals still is a limitation for using skin temperature to monitor and assess responses to exercise. If basal skin temperature proves to be a useful indicator of muscle damage, physiological stress or low adaptation of training workload, its monitoring could be interesting for the periodization of training loads and the prevention of over-training syndrome.

One of the main differences between these studies is the condition of the participants during the day when skin temperature was determined. Whereas de Andrade Fernandes et al. (2017) measured during a national championship qualification period when players were concentrated together during all the days of testing (de Andrade Fernandes et al., 2017), the two other studies had participants coming to the laboratory for the measurements (Pérez-Guarner et al., 2019; Silva et al., 2018), and therefore, no strict control or information about what the participant did during the day was possible. Skin temperature can be affected by a number of daily routine factors, including but not limited to nutrition, hours of rest, and amount of daily activity (Fernández-Cuevas et al., 2015; Priego Quesada et al., 2017). In this regard, monitoring skin temperature responses during a training camp could result in a better control of the inter-participant variability and minimizes the impact of all these factors with the goal of investigating the use of skin temperature as a tool to monitor exercise recovery.

Therefore, the aim of this preliminary study was to determine regional skin temperatures of triathletes participating in a training camp with cumulative training load.

2. Materials and methods

2.1. Participants

Ten male recreational triathletes participated in the study. The sample was formed by convenience after contact with an amateur team in the last loading period before tapering to competition. For this preliminary study, the sample size was defined using the model of Hopkins (2002) (change in the mean in a crossover study) looking for effect sizes larger than 0.8 in the skin temperature increments during days. Participants' age, body mass, height, body fat percentage, muscle mass percentage, body mass index were (mean ± standard deviation), 40 ± 6 years old, 78 ± 12 kg, 1.76 ± 0.04 m, 14 ± 5%, 63 ± 6%, 25.1 ± 3.7 kg/m², respectively. Body mass, body fat percentage and muscle mass percentage was determined by bioelectrical impedance analysis (OMRON BF511, Healthcare Co., Kyoto, Japan). Their triathlon experience was 7 ± 3 years and their running, cycling, and swimming weekly training volumes (recorded using training applications) were 28 ± 12 km, 159 ± 61 km and 5 ± 2 km, respectively. Exclusion

criteria were the development of any injury or disease during the previous month to the training camp. To participate in the study, all participants signed a written consent form. This research protocol is in accordance with the Declaration of Helsinki and was approved by the local University Ethics Committee. In order to reduce skin temperature variability, participants were instructed to avoid smoking, drinking alcohol, caffeine, or other stimulant beverages, meals, ointments, cosmetics, sunbathing, physiotherapy treatments and showering for 4 h before the assessments (Moreira et al., 2017). In addition, they were instructed to avoid high intensity physical activity in the 24 h before the first assessment. The participants confirmed the compliance of each of the instructions on each day of measurement.

2.2. Procedures

The training camp was held in Denia (Spain) between March 28th and 31st 2019. Fig. 1 details the program, exercise workload, and schedule of the training camp. The experimental design included 3 days of testing: before the start of the training (Test_{pre}), one day after (Test₁), and two days after start of the training (Test₂). Measurements were always performed in the morning (between 07:45–08:30 a.m.) before the breakfast in order to minimize the effects of the circadian rhythm (Marins et al., 2015). The measurements from each day of testing included perception of pain and fatigue, skin temperature, and jump performance. After training sessions, participants did not perform

| | |
|------------------------|--|
| 28 th March | <ul style="list-style-type: none"> • 20:30 Presentation of the training camp • 21:15 Dinner |
| 29 th March | <ul style="list-style-type: none"> • 07:45 Measurements (Test_{pre}) • 08:30 Breakfast • 09:00 Training cycling: 94 kms at an intensity of 70% VO_{2max} including 6k of uphill time trial all-out. 1800 meters of swimming in the sea at an intensity of 60-70% VO_{2max} • 13:30 Lunch • 14:30 Lunch • 17:15 Core training session (45 min) • 18:45 Technical classroom • 21:15 Dinner |
| 30 th March | <ul style="list-style-type: none"> • 07:45 Measurements (Test₁) • 08:30 Breakfast • 09:00 Training cycling: 156 km + 2977 elevation m. 60% of the route at 60-70% VO_{2max} and 40% of the route at 71-85% VO_{2max} (uphills) • 15:30 Lunch • 17:15 Joint mobility session, no cardiovascular and strength effort (45 min) • 18:45 Technical classroom • 21:15 Dinner |
| 31 th March | <ul style="list-style-type: none"> • 07:45 Measurements (Test₂) • 08:30 Breakfast • 10:00 Closure training camp |

Fig. 1. Training camp schedule.

recovery or physiotherapy sessions (e.g. massage, cryotherapy, etc.) to avoid the effect of these interventions on body and skin temperature.

2.3. Fatigue and pain perception

Perception of fatigue and pain were measured using a 150-mm visual analogue scale (VAS) (Mündermann et al., 2002). The scales were labeled from the left as “absence of fatigue/pain” (0 mm) to the right as “highest fatigue/pain imaginable” (150 mm). Fatigue and pain were measured considering different body regions: 1) overall, 2) trunk and upper limbs, 3) buttocks, 4) thigh, 5) knee, and 6) leg and foot.

2.4. Skin temperature

Skin temperature was assessed using an infrared thermal camera (E-60, Flir Systems Inc., Wilsonville, OR, USA) with noise-equivalent temperature difference (NETD) < 0.05 °C, focal plane sensor array size of 320x240, and measurement uncertainty of $\pm 2\%$ of the overall operational temperature range (Vardasca, 2018). Before starting the study, camera calibration was checked using a black body (BX-500 IR Infrared Calibrator, CEM, Shenzhen, China). In order to ensure the quality of the thermography assessment, a TISEM checklist was used to certify that all important aspects were attended (Moreira et al., 2017). All images were taken by the same trained thermography technician (Level I thermographer accredited by the Infrared Training Center). The camera was turned on 10 min before the measures to ensure its stabilization and positioned 1.5 m far from the participant, perpendicular to the body regions of interest (ROI). Thermal images were recorded after 10 min of the participant resting standing up wearing upper and lower limbs uncovered so as to adapt to the room temperature (Marins et al., 2014). Room temperature and relative air humidity determined by a thermohygrometer (digital thermohygrometer, TFA Dostmann, Wertheim-Reicholzheim, Germany) were added to the camera setup. Environmental room conditions were 18 °C in all the tests and 44%, 54% and 63% of relative humidity for the Test_{pre}, Test₁ and Test₂, respectively. For all the days, the maximum environmental outdoor temperature was 18 °C and the average 12 °C.

The mean temperature, the maximum temperature and the standard

deviation of 8 ROIs from the upper and lower limbs (Fig. 2) were obtained using a thermography software (Thermacam Researcher Pro 2.10 software, FLIR, Wilsonville, Oregon, USA). The emissivity was set at 0.98 (Steketee, 1973).

2.5. Jump performance

Jump height was assessed as a measure of lower limbs performance. Participant performed the Counter Movement Jump test (CMJ) using a contact mat (model DIN-A3, Chronojump Bosco-System®, Barcelona, Spain). Before jump assessment participants performed a warm-up consisting of 15–20 squat exercise repetitions. They were instructed to jump as high as possible using the following technique: 1) to hold a start position from a standing posture with the hands placed at the hips in order to minimize the influence of arms' movements, 2) to perform a quick semi-squat movement reaching 90° of knee flexion, and 3) to perform the fastest possible upward movement to jump as high as possible and land on their toes. Each participant completed 3 repetitions of the CMJ performed with a rest interval of 30 s between repetitions. The mean of the 3 jumps was used for analyzing jump height.

2.6. Statistical analysis

Statistical analysis was performed using SPSS 21.0 (IBM Armonk, New York, USA). Data are reported as mean \pm standard deviation with 95% confidence intervals of the differences between measurement days (CI95%). The normality of data distribution was checked using the Shapiro-Wilk test. Repeated measures ANOVA were applied for CMJ and pain/fatigue perception to assess the difference between measurement days (Test_{pre} vs. Test₁ vs. Test₂). The same statistical approach was performed for skin temperature data, but considering two factors: measurement day and limb side (right vs. left). When main effects were found, the Bonferroni post hoc test was applied to identify the differences. The significance level was set at $p < 0.05$. Cohen's effect sizes (ES) were computed and classified as small (ES 0.2–0.5), moderate (ES 0.5–0.8), or large (ES > 0.8) (Cohen, 1988). Finally, stepwise multiple linear regressions were performed to examine the relationships between skin temperature variations (ΔT_{24} , ΔT_{48}) and the

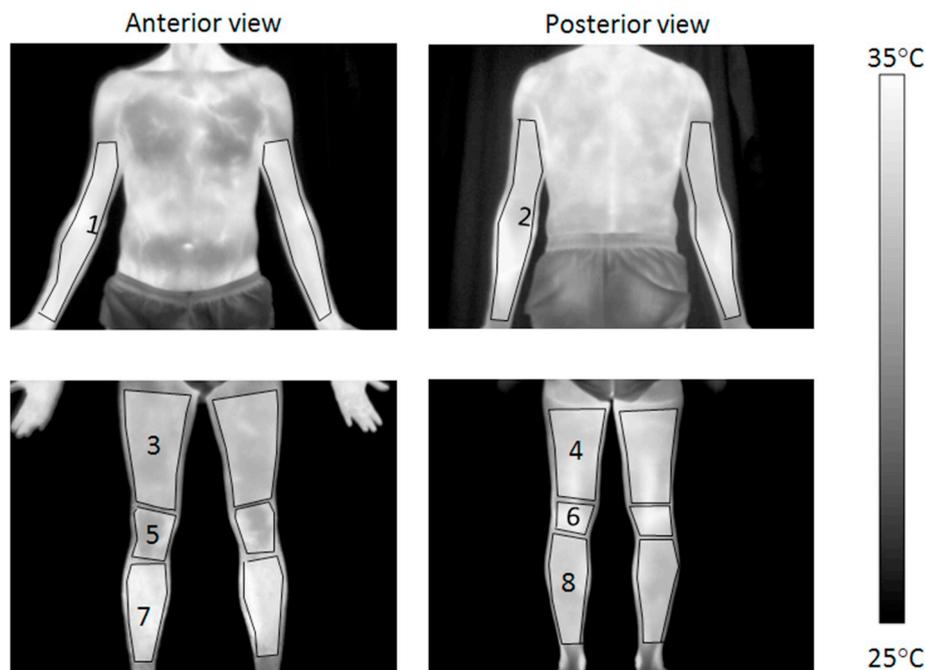


Fig. 2. Regions of interest for thermography measurements: 1) anterior upper limbs, 2) posterior upper limbs, 3) anterior thigh, 4) posterior thigh, 5) anterior knee, 6) posterior knee, 7) anterior leg, and 8) posterior leg.

other outcomes. Considering skin temperature variation from each ROI, the model considered demographic variables of age, muscle mass percentage, running weekly training volume, cycling weekly training volume, and swimming weekly training volume, the correspondent region of perception of fatigue and pain variation, and jump height variation as input variables. For the models obtained, coefficient of each variable of the equation, percentage of the variance explained by the model (R^2) and significance value of the model were provided.

3. Results

3.1. Effects of cumulative training

The total time of exercise considering the exercise sessions was 270 and 420 min in the first and second days of training, respectively. All participants completed all the sessions. Self reported sleep time was 420 ± 46 min per night.

Jump height did not differ between the measurements $Test_{pre}$ 25.4 ± 3.6 cm vs. $Test_1$ 25.2 ± 3.6 cm vs. $Test_2$ 26.0 ± 3.5 cm ($p > 0.05$). Fatigue perception was higher after training in most of the body regions (e.g. overall fatigue: $Test_{pre}$ vs. $Test_1$ CI95% [0.1, 4.4 cm] $p = 0.04$ and $ES = 0.9$; $Test_{pre}$ vs. $Test_2$ CI95% [1.2, 5.9 cm] $p < 0.01$ and $ES = 1.3$; Fig. 3A). Fatigue perception was higher in the $Test_2$ than

in the $Test_1$ in overall, thigh (CI95% [0.2, 2.0 cm] $p = 0.02$ and $ES = 0.4$) and leg/foot (CI95% [0.1, 1.6 cm] $p = 0.03$ and $ES = 0.3$). Although the muscles spanning knee joint did not show a significant increase in fatigue perception ($p > 0.05$), it showed a large effect size of $Test_{pre}$ with the other two tests ($ES > 1.1$). Pain perception was higher in the $Test_2$ than in the $Test_{pre}$ in all the regions except for the overall perception (e.g. thigh: CI95% [0.7, 4.9 cm] $p = 0.01$ and $ES = 1.9$; Fig. 3B).

Factor limb side was not significant for any ROI and any skin temperature parameter ($p > 0.05$). Then, results are presented without considering this factor in the analysis. Mean skin temperature increased after training in all the ROIs (e.g. anterior upper limb: $Test_{pre}$ vs. $Test_1$ CI95% [0.1, 0.9 °C] $p = 0.04$ and $ES = 0.8$; $Test_{pre}$ vs. $Test_2$ CI95% [0.2, 1.4 °C] $p < 0.01$ and $ES = 1.4$; Fig. 4A). Maximum skin temperature also increased in posterior upper limb, posterior thigh, posterior knee and posterior leg (e.g. posterior upper limb: $Test_{pre}$ vs. $Test_1$ CI95% [0.1, 1.0 °C] $p = 0.01$ and $ES = 1.2$; $Test_{pre}$ vs. $Test_2$ CI95% [0.3, 1.5 °C] $p < 0.01$ and $ES = 1.5$; Fig. 4B). Although the anterior knee presented a lower standard deviation in the $Test_1$ than the $Test_{pre}$ (CI95% [0.1, 0.2 °C] $p = 0.02$ and $ES = 0.8$) the other seven ROIs presented similar standard deviation values in the different measurement days ($p > 0.05$; Fig. 4C).

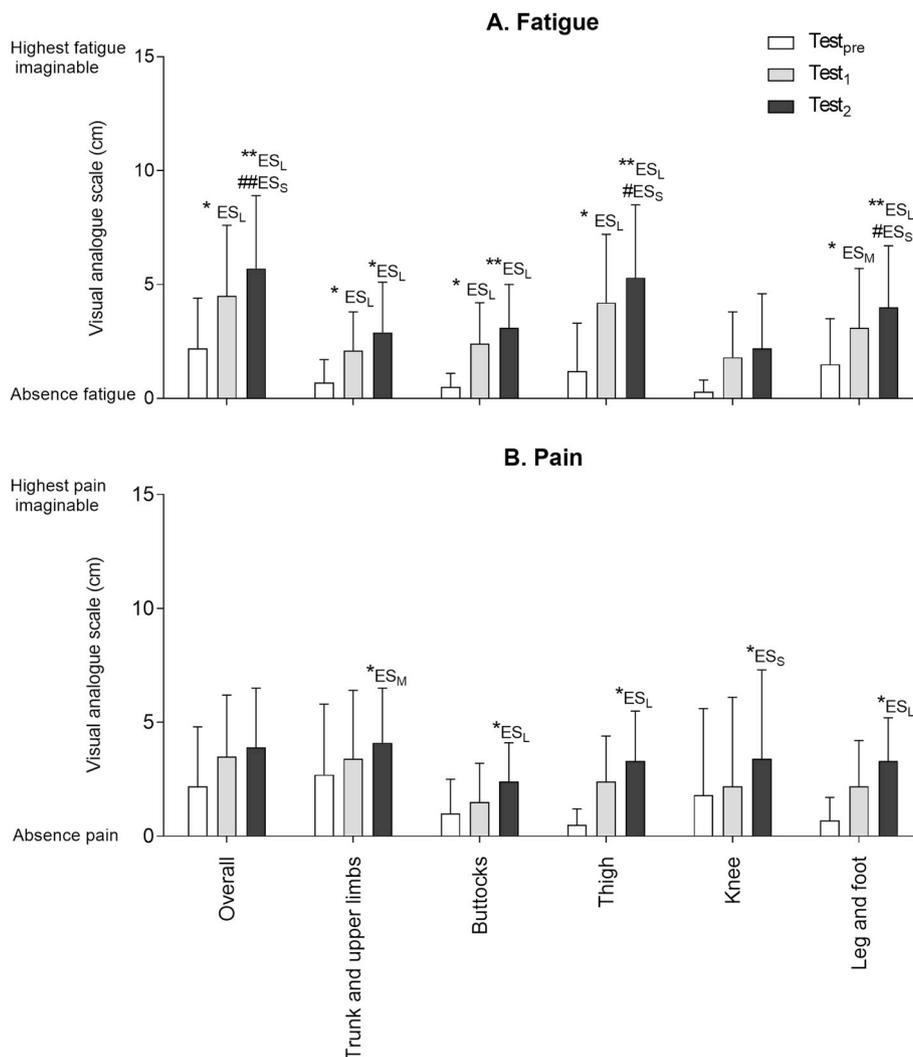


Fig. 3. Mean (bars) and standard deviation (vertical lines) results of perceived fatigue (A) and pain (B) before start the training ($Test_{pre}$), after one day ($Test_1$), and two consecutive days of training ($Test_2$). The highest fatigue/pain imaginable was set at 15 cm. Differences are identified by symbols (* $p < 0.05$ compared to $Test_{pre}$; ** $p < 0.01$ compared to $Test_{pre}$; # $p < 0.05$ compared to $Test_1$; ## $p < 0.01$ compared to $Test_1$) and the effect size (large effect size ES_L ; moderate effect size ES_M ; small effect size ES_S).

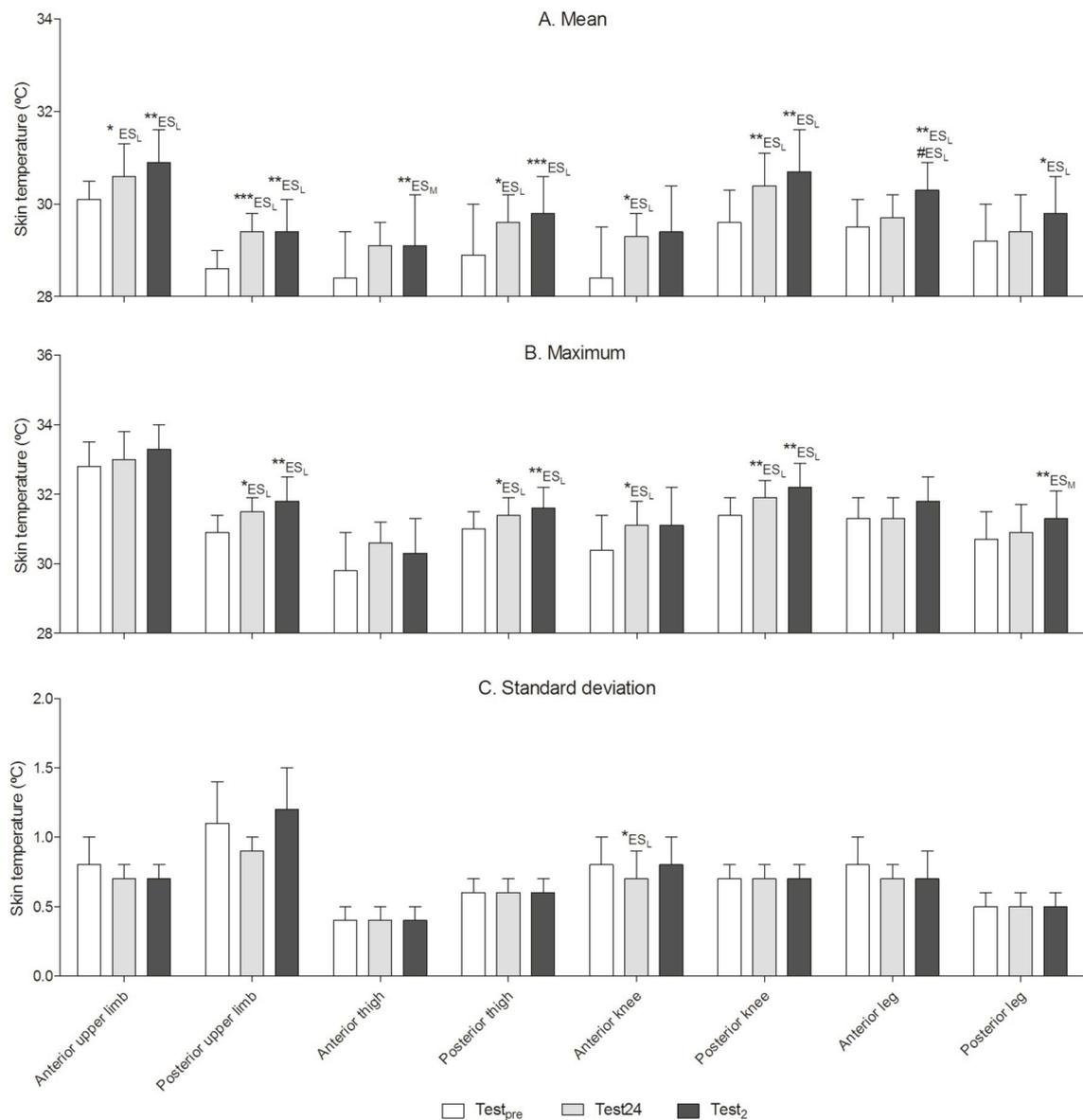


Fig. 4. Mean (bars) and standard deviation (vertical lines) result of the mean (A), maximum (B) and standard deviation (C) skin temperature measurements in the measurement test before start the training (Test_{pre}), after one day (Test₁), and two consecutive days of training (Test₂). The highest fatigue/pain imaginable was set at 15 cm. Differences are identified by symbols (*p < 0.05 compared to Test_{pre}; **p < 0.01 compared to Test_{pre}; #p < 0.05 compared to Test₁; ##p < 0.01 compared to Test₁) and the effect size (large effect size ES_L; moderate effect size ES_M; small effect size ES_S).

3.2. Relationship between skin temperature variation and demographic data, perception of fatigue and pain, and jump height

The multiple linear regressions indicated that skin temperature was directly related with muscle mass percentage in the anterior and posterior thigh regions, with reported weekly training volume in the posterior knee and in the posterior leg regions, and inversely related with the perception of fatigue at muscles spanning the knee joint (Table 1).

4. Discussion

The objective of this study was to determine the regional skin temperatures of triathletes during a training camp with cumulative training load. Athletes were training together during two days under very similar conditions, and the measurements were conducted at specific time points before, during and after the training sessions. This is one of the few studies that conducted experiments applying infrared thermography under strict conditions of control of the participant's

daily routine (for instance, in a concentration or living in a military base) (de Andrade Fernandes et al., 2017; Marins et al., 2015), including not only training characteristics, but also recovery, sleep, and food intake. Our main findings are the acute increase in mean and maximum skin temperature after the first and second day of training for most of the body regions, and the correlation between skin temperature response at specific body regions with muscle mass percentage, reported weekly training volume, and perception of fatigue.

The relationship between training load and changes in skin temperature is controversial in the literature. An increase of ~1 °C and ~1.5 °C in the 24 h after one and two consecutive soccer matches, respectively, was described for soccer players (de Andrade Fernandes et al., 2017). Two other studies observed no difference in skin temperature 48 h after a calf raise protocol to induce muscle soreness (Silva et al., 2018), and 24 and 48 h after a half marathon competition (Pérez-Guarner et al., 2019). We observed an increase in skin temperature between 0.5 and 1 °C during a 2 days triathlon training camp. Therefore, it is important to highlight the possible causes of the discrepancies

Table 1

Regressions models obtained by the multivariate stepwise regression analyses between variations in skin temperature (ΔT_{24} , ΔT_{48}) and other outcomes from the study.

| Regression model obtained | | | |
|-----------------------------------|-------------------------------------|-----------------------|--------------------------|
| Region of interest | Variable | Coefficient [CI95%] | R ² (p value) |
| ΔT_{24} | | | |
| Anterior upper limbs | Any variable was included | | |
| Posterior upper limbs | Any variable was included | | |
| Anterior thigh | Intercept | -6.85 [-11.26, -2.43] | 0.7 (< 0.01) |
| | Muscle mass percentage | 0.12 [0.05, 0.19] | |
| Posterior thigh | Intercept | -5.44 [-8.55, -2.33] | 0.7 (< 0.01) |
| | Muscle mass percentage | 0.10 [0.05, 0.15] | |
| Anterior knee | Any variable was included | | |
| Posterior knee | Intercept | -0.75 [-1.64, 0.14] | 0.7 (< 0.01) |
| | Cycling weekly training volume | 0.01 [0.00, 0.01] | |
| | Running weekly training volume | 0.02 [0.00, 0.04] | |
| Anterior leg | Any variable was included | | |
| Posterior leg | Intercept | -0.64 [-1.45, 0.22] | 0.44 (0.04) |
| | Cycling weekly training volume | 0.01 [0.00, 0.01] | |
| ΔT_{48} | | | |
| Anterior upper limbs | Any variable was included | | |
| Posterior upper limbs | Any variable was included | | |
| Anterior thigh | Any variable was included | | |
| Posterior thigh | Intercept | -3.02 [-6.05, 0.01] | 0.5 (0.02) |
| | Muscle mass percentage | 0.06 [0.01, 0.11] | |
| Anterior knee | Intercept | 1.32 [0.95, 1.68] | 0.5 (0.03) |
| | Δ knee_fatigue ₄₈ | -0.14 [-0.27, -0.02] | |
| Posterior knee | Any variable was included | | |
| Anterior leg | Any variable was included | | |
| Posterior leg | Any variable was included | | |

between these studies in order to propose future investigations that may help to clarify whether basal skin temperature could be an outcome related with the training load from the previous days.

One possible explanation to the difference in outcomes between the studies can be the inter-participant variability. Skin temperature is dependent of many intrinsic and extrinsic factors (Fernández-Cuevas et al., 2015; Priego Quesada et al., 2017). These factors must be taken into account when recruiting participants (e.g. including only non-smokers participants or participants with similar level of physical fitness) or providing instructions to the participants follow before the measurements (e.g. to avoid large meals or caffeine in the previous hours of the measurement) (Moreira et al., 2017; Priego Quesada et al., 2017). However, when all the participants are living together, having the same daily activity, dietary, and sleep routine, a better control of these factors and a lower inter-participant variability could be expected. It may help to explain the results from our study and the study performed during a concentration period of a soccer national team (de Andrade Fernandes et al., 2017). In other studies participants received instructions but every participant had a different life routine (Pérez-Guarner et al., 2019; Silva et al., 2018). Future studies could explore whether skin temperature measurements significantly rely on these aspects by comparing measurements in the different conditions illustrated by the studies but considering the same subjects.

Another possible explanation is the moment of measurement. Circadian rhythm affects skin blood flow and then skin temperature (Costa et al., 2015; Marins et al., 2015; Smolander et al., 1993). Skin blood flow is lower in the morning and increases during the day, and this effect was observed mainly in the skin temperature of the distal body areas such as hands or feet (Costa et al., 2015; Smolander et al., 1993). If training increases skin blood flow in the consecutive days of activity (Naylor et al., 2016), a hypothesis could be that measuring skin temperature in the morning and before breakfast when blood flow is lower, as performed in the present study, could better reflect the effect of training on skin temperature. However, this possible explanation is not clear observing the methodology and results from previous studies. Although one study presented skin temperature increments in the day after exercise (de Andrade Fernandes et al., 2017) and the others not

(Pérez-Guarner et al., 2019; Silva et al., 2018), all reported measurements made in the afternoon. It is worthy of investigation whether changes in skin temperature in response to exercise and measured during morning are more sensitive to the training effect than when the measurements are performed in the afternoon.

The last main explanation that we propose is a possible different effect of training on skin temperature considering the presence of muscle damage or not. Da Silva et al. (2018) induced muscle damage, which was evident by the different measurements performed by the authors. Also Pérez-Guarner et al. (2019) reported increase in markers of muscle damage after completing a half marathon. Although these markers would theoretically be associated with local muscle responses related to inflammation that would influence local muscle temperature, in both cases the muscle damage did not correlate with skin temperature. Pain could result in skin vasoconstriction (Burton et al., 2016) and then counteract the possible effect of inflammation. One hypothesis could be that when muscle damage is produced, some people may experience skin vasoconstriction due to the increase in skin sympathetic nerve activity (Burton et al., 2016). If pain is not perceived, inter-participant variability in skin temperature response could be lower, and training volume could result in an increase of skin blood flow. Our data may support this hypothesis. The values of perception of fatigue and pain in our study could be interpreted as lower than those from previous studies (Pérez-Guarner et al., 2019; Silva et al., 2018), and jump performance did not differ between the training days. Our participants experienced a higher training volume (> 270 min per day) than the previous studies including soccer (max 90 min/day) (de Andrade Fernandes et al., 2017), half marathon (mean of 101 min) (Pérez-Guarner et al., 2019), and calf raise exercise (< 30 min) (Silva et al., 2018). Finally, we found that participants with a higher muscle mass and a higher reported weekly training volume also showed a higher responses of skin temperature due to the cumulative training. A higher training volume is associated with higher pain threshold and higher pain tolerance (Hakansson et al., 2018; Jones et al., 2014), which is in agreement with the relationships observed and the explanation that we propose to our results. However, it is important to mention that this possible explanation is speculative and future research is needed to test

these hypotheses.

Maximum skin temperature was suggested as more sensitive to changes related to the blood flow and inflammation than mean skin temperature (Formenti et al., 2018; Ludwig et al., 2014). Our results show the opposite, because the differences between measurement days were observed in all the regions, and clearly in the assessment of mean skin temperature. However, it is important to mention that maximum temperature was calculated using information from a single pixel. In this regard, if in one day a ROI has only one pixel showing a value of 34 °C, and all the other pixels are below 32°, and in the other day there are more pixels with values of 34 °C, the maximum temperature would not be a good representation of these differences. To solve this issue other estimations are proposed, for example considering the mean of the 125 warmest pixels in the ROI (called Tmax method), which would present lower noise (Formenti et al., 2018). We did not apply the Tmax method because the commercial software used did not have this possibility.

Our study has inherent limitation. We considered skin temperature before training measuring only one day. Additional measures in days prior to training start could improve the accuracy of basal state of the participants. The measurement of physiological parameters such as muscle damage, muscle temperature or skin blood flow would also help to interpret the results, as well as the inclusion of a control group not training during the days of measure. In addition, in order to measure the effect of cumulative load, two experimental groups could be suggested, one with only one day of training, and other with cumulative training resulting of two consecutive sessions. For these reasons, our investigation was considered a preliminary study to help future studies. A thermal stress (e.g. cooling the skin) could provide interesting data about the perfusion capacity and its measurement can be implemented in future studies. Although sample size was small (n = 10), large effect size were observed in most cases and a high percentage of the variance were explained by most of the regressions obtained. Then, we consider that our results are consistent and open room for future research that should consider a higher sample size including sex, age, and physical fitness condition stratification in the data analysis and interpretation. The approach conducted in this study and considering the limitations mentioned provides a relevant context to find out whether it is possible to apply the infrared thermography to monitor skin temperature and to use this information to help in the periodization of training loads and the prevention of overtraining syndrome.

5. Conclusion

Basal skin temperatures increase after cumulative exercise during a training camp. We consider the importance of controlling intrinsic and extrinsic factors in the skin temperature assessment, to measure temperature in the morning, and the lack of muscle damage as possible explanations of our results in comparison with previous studies. These preliminary results open room for future research aiming to understand the factors influencing the relationship between training load and skin temperature response during consecutive days of training.

Declarations of interest

None.

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References

- Amano, T., Ichinose, M., Inoue, Y., Nishiyasu, T., Koga, S., Kenny, G.P., Kondo, N., 2016. Influence of forearm muscle metaboreceptor activation on sweating and cutaneous vascular responses during dynamic exercise. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 310, R1332–R1339. <https://doi.org/10.1152/ajpregu.00545.2015>.
- Ammer, K., Formenti, D., 2016. Does the type of skin temperature distribution matter? *Thermol. Int.* 26, 51–54.
- Burton, A.R., Fazalbhoy, A., Macefield, V.G., 2016. Sympathetic responses to noxious stimulation of muscle and skin. *Front. Neurol.* 7. <https://doi.org/10.3389/fneur.2016.00109>.
- Cheuvront, S.N., Kenefick, R.W., Montain, S.J., Sawka, M.N., 2010. Mechanisms of aerobic performance impairment with heat stress and dehydration. *J. Appl. Physiol.* Bethesda Md 109, 1989–1995. <https://doi.org/10.1152/jappphysiol.00367.2010.1985>.
- Cohen, J., 1988. *Statistical Power Analysis for the Behavioral Sciences*, second ed. Routledge.
- Costa, C.M.A., Sillero-Quintana, M., Piñonosa Cano, S., Moreira, D.G., Brito, C.J., Fernandes, A.A., Pussieldi, G.A., Marins, J.C.B., 2015. Daily oscillations of skin temperature in military personnel using thermography. *J. R. Army Med. Corps.* <https://doi.org/10.1136/jramc-2015-000462>.
- Cramer, M.N., Jay, O., 2016. Biophysical aspects of human thermoregulation during heat stress. *Auton. Neurosci. Basic Clin.* 196, 3–13. <https://doi.org/10.1016/j.autneu.2016.03.001>.
- 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, 635–643.
- Fernández-Cuevas, I., Bouzas Marins, J.C., Arnáiz Lastras, J., Gómez Carmona, P.M., Piñonosa Cano, S., García-Concepción, M.A., 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>.
- Fernández-Cuevas, I., Sillero-Quintana, M., García-Concepción, M.A., Serrano, J.R., Gómez-Carmona, P., Marins, J.B., 2014. Monitoring skin thermal response to training with infrared thermography. *N. Stud. Athl.* 29, 57–71.
- Formenti, D., Ludwig, N., Rossi, A., Trecroci, A., Alberti, G., Gargano, M., Merla, A., Ammer, K., Caumo, A., 2018. Is the maximum value in the region of interest a reliable indicator of skin temperature? *Infrared Phys. Technol.* 94, 299–304.
- González-Alonso, J., Calbet, J.A.L., Boushel, R., Helge, J.W., Søndergaard, H., Munch-Andersen, T., van Hall, G., Mortensen, S.P., Secher, N.H., 2015. Blood temperature and perfusion to exercising and non-exercising human limbs. *Exp. Physiol.* 100, 1118–1131. <https://doi.org/10.1113/EP085383>.
- Hakansson, S., Jones, M.D., Ristov, M., Marcos, L., Clark, T., Ram, A., Morey, R., Franklin, A., McCarthy, C., Carli, L.D., Ward, R., Keech, A., 2018. Intensity-dependent effects of aerobic training on pressure pain threshold in overweight men: a randomized trial. *Eur. J. Pain Lond. Engl.* 22, 1813–1823. <https://doi.org/10.1002/ejp.1277>.
- Hildebrandt, C., Raschner, C., Ammer, K., 2010. An overview of recent application of medical infrared thermography in sports medicine in Austria. *Sensors* 10, 4700–4715.
- Hopkins, W.G., 2002. Scale of magnitudes for effect statistics. In: *A New View of Statistics*, (Auckland).
- Jones, M.D., Booth, J., Taylor, J.L., Barry, B.K., 2014. Aerobic training increases pain tolerance in healthy individuals. *Med. Sci. Sport. Exerc.* 46, 1640–1647. <https://doi.org/10.1249/MSS.0000000000000273>.
- Lahiri, B.B., Bagavathiappan, S., Jayakumar, T., Philip, J., 2012. Medical applications of infrared thermography: a review. *Infrared Phys. Technol.* 55, 221–235.
- Lei, J., You, H.-J., Andersen, O.K., Graven-Nielsen, T., Arendt-Nielsen, L., 2008. Homotopic and heterotopic variation in skin blood flow and temperature following experimental muscle pain in humans. *Brain Res.* 1232, 85–93. <https://doi.org/10.1016/j.brainres.2008.07.056>.
- Ludwig, N., Formenti, D., Gargano, M., Alberti, G., 2014. Skin temperature evaluation by infrared thermography: comparison of image analysis methods. *Infrared Phys. Technol.* 62, 1–6.
- Marins, J.C.B., Formenti, D., Costa, C.M.A., de Andrade Fernandes, A., Sillero-Quintana, M., 2015. Circadian and gender differences in skin temperature in militaries by thermography. *Infrared Phys. Technol.* 71, 322–328. <https://doi.org/10.1016/j.infrared.2015.05.008>.
- 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>.
- 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., Merla, A., Pascoe, D.D., Priego Quesada, J.I., Schwartz, R.G., Seixas, A.R.D., Selfe, J., Vainer, B.G., Sillero-Quintana, M., 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>.
- Mündermann, A., Nigg, B.M., Stefanyshyn, D.J., Humble, R.N., 2002. Development of a reliable method to assess footwear comfort during running. *Gait Posture* 16, 38–45.
- Naylor, L.H., Davis, E.A., Kalic, R.J., Paramalingam, N., Abraham, M.B., Jones, T.W., Green, D.J., 2016. Exercise training improves vascular function in adolescents with type 2 diabetes. *Phys. Rep.* 4, e12713. <https://doi.org/10.14814/phy2.12713>.
- Paull, G., Dervis, S., McGinn, R., Haqani, B., Flouris, A.D., Kondo, N., Kenny, G.P., 2015.

- Muscle metaboreceptors modulate postexercise sweating, but not cutaneous blood flow, independent of baroreceptor loading status. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 309, R1415–R1424. <https://doi.org/10.1152/ajpregu.00287.2015>.
- 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 034009–034019. <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, Cham, Switzerland, pp. 49–79.
- Ring, E.F.J., Ammer, K., 2012. Infrared thermal imaging in medicine. *Physiol. Meas.* 33, R33–R46. <https://doi.org/10.1088/0967-3334/33/3/R33>.
- Schlager, O., Gschwandtner, M.E., Herberg, K., Frohner, T., Schillinger, M., Koppensteiner, R., Mlekusch, W., 2010. Correlation of infrared thermography and skin perfusion in Raynaud patients and in healthy controls. *Microvasc. Res.* 80, 54–57.
- Silva, W. da, 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, 104007. <https://doi.org/10.1088/1361-6579/aae6df>.
- Smolander, J., Härmä, M., Lindgvist, A., Kolari, P., Laitinen, L.A., 1993. Circadian variation in peripheral blood flow in relation to core temperature at rest. *Eur. J. Appl. Physiol.* 67, 192–196. <https://doi.org/10.1007/BF00376666>.
- Steketee, J., 1973. Spectral emissivity of skin and pericardium. *Phys. Med. Biol.* 18, 686.
- Stöcker, F., Oldershausen, C.V., Paternoster, F.K., Schulz, T., Oberhoffer, R., 2018. Does postexercise modelled capillary blood flow accurately reflect cardiovascular effects by different exercise intensities? *Clin. Physiol. Funct. Imaging* 38, 431–438. <https://doi.org/10.1111/cpf.12434>.
- Vardasca, R., 2018. The lack of terminology agreement in describing infrared cameras at scientific writing. *Thermol. Int.* 28, 48–49.



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