REVIEW ARTICLE

https://doi.org/10.6063/motricidade.21116

The use of infrared thermography in endurance athletes: a systematic review

A utilização da termografia infravermelha em atletas de endurance: uma revisão sistemática

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ABSTRACT

Infrared thermography has become increasingly common in sports assessment and has grown a lot over the past few years. Our objective was to identify the assessment protocols and the skin temperature behavior of practitioners of endurance sports. A systematic review was carried out following the PRISMA recommendations between the 1st and the 31st of March 2020, at MEDLINE, LILACS, SCOPUS, SPORT Discus, CINAHL, Web of Science, Science Direct, Cochrane, and Scielo, using combinations with 11 descriptors for "thermography" and 6 descriptors for "endurance training". It was identified 24 different regions of interest evaluated region in endurance sports. The acclimatization time was respected in 75% of the selected studies, and the thermal images were acquired predominantly in three moments: before the test, immediately after the test, and 10 minutes after the test. It was observed that Tskin decreased in the initial moments and increased after exercise. It can be concluded that the regions of interest used were mostly the specific muscle recruited in each modality, with emphasis on the muscle groups of the lower limbs, and after this initial decrease in temperature, the thermal response is mainly dependent on the duration and intensity of exercise.

KEYWORDS: endurance training; thermography; cycling; running.

INTRODUCTION

Maintaining physical performance, especially in long-term events, requires meticulous preparation (Hermand, Chabert, & Hue., 2019), and the physiological imbalance can result in muscle fatigue, damage, and changes in the systemic inflammatory response (Mara et al., 2013).

The achieved performance during prolonged exercise depends on several physiological factors: (a) the capacity to produce and use energy in a fast and prolonged way (Arellano & Kram, 2014) (b) the oxygen uptake ($\dot{V}O_2\ max$) as an indicator of the athlete's ability to generate energy in the medium and long terms, and (c) the energy cost that represent the economy of energy expenditure at high intensity (Swinnen, Kipp, & Kram, 2018).

Another factor related to performance is the skin temperature's ability to dissipate heat in muscle efforts (Bertucci, Arfaoui, Janson, & Polidori, 2013a; Ludwig et al., 2016), transferring the heat from the deepest tissues to the surface (Ammer & Formenti, 2016). At rest, it varies between 34°C and 36°C (Raymann, Swaab, & Van Someren, 2008), and it is performed by changes in the vascular tone of the skin and increased sweating. The blood flow is directed to the active muscles and the myocardium in order to supply their metabolic needs (Akimov & Son'kin, 2011).

The evaporation of sweat represents the main mechanism to reduce skin temperature during exercise (Chudecka & Lubkowska, 2010). At the beginning of the exercise, there may be a reduction in temperature due to sweating on the

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Conflict of interest: nothing to declare. Funding: nothing to declare.
Received: 10/05/2020. Accepted: 01/30/2021.

skin surface and the use of blood in the required muscles (Fernandes et al., 2012). However, in endurance sports, a constant increase in central temperature (Tcore) and skin temperature (Tskin) is observed, especially in high-temperature environments, which limits the performance and can increase the risk of exhaustion and heat stroke (Nybo, 2010).

To analyze the thermoregulation process and understand how this energy is dissipated, infrared thermography (IRT) can be used (Arfaoui, Polidori, Taiar, & Pop, 2012). Its main advantages are the non-invasive method; monitoring a specific region of interest (local analysis) or throughout the body (global analysis); freedom of movement during exercise; the lack of interference in the processes of heat loss by radiation, convection and evaporation; the accuracy; reproducibility; and the possibility of recording videos, with certain camera models (Fernandes et al., 2014).

Although the number of studies with IRT has increased in the last decade (Moreira et al., 2017), some methodological aspects remain controversial. One of them is the definition of regions of interest (ROIs) in thermal images because the Tskin can be affected by several factors of the daily routine, including nutrition, sweating, hours of sleep, and physical activity, as well as environmental factors (Fernández-Cuevas et al., 2015).

Working with athlete evaluation requires a careful evaluation to not interfere with the training routine and competitions. So, the definition of the evaluation moments and the adjustments to the protocols are extremely important to minimize interference in the athlete's routine. Previous systematic reviews (Jimenez-Pavon et al., 2019; Fernández-Cuevas et al., 2015; Fernandes et al., 2012) concluded the effectiveness of checking Tskin using IRT. However, none of these reviews detailed the assessment protocols and Tskin behavior of endurance sports practitioners. As a result of this knowledge gap, the aim of this study was to identify the assessment protocols and the Tskin behavior of endurance sports practitioners.

METHODS

Protocol and register

This systematic review was written according to the PRISMA recommendations (Moher, Liberati, Tetzlaff, & Altman, 2015) and was registered in the International Prospective Register of Systematic Reviews (PROSPERO) under number CRD4202018493.

Inclusion criteria

In this systematic review, experimental studies were included that met the following inclusion criteria (Moola et al., 2015): studies related to endurance sports, with trained athletes, of both sexes and aged between 16 and 49 years. In the outcome, the type of camera used, the ROIs of interest, the used protocols, and the results were considered.

Search strategy

The search occurred from March 1st to March 31st, 2020, in the National Library of Medicine (MEDLINE), Latin American and Caribbean Literature in Health Sciences (LILACS), SCOPUS, SPORT Discus, Cumulative Index to Nursing and Allied Health Literature (CINAHL), Web of Science, Science Direct, Cochrane and Scielo. The following keywords were used as descriptors for Medical Subject Headings (MeSH) or words in the text: thermography, skin temperature, infrared image, endurance sports, cycling, running, marathon, triathlon, and their synonyms. The following search phrase was obtained using the Boolean logic operators "AND" between descriptors and "OR" between synonyms: *"Thermography" OR "Skin Temperature" OR "Skin thermal" OR "Infrared imaging" OR "Infrared thermography" OR "Infrared Camera" OR "Thermographic pictures" OR "Thermographic images" OR "Thermal images" AND " Endurance training" OR "Bicycling" OR "Running" OR "Marathon" OR "Triathlon"*. In addition, bibliographic references from other sources were explored to find studies that, perhaps, have not been retrieved from the databases.

Studies selection

Two independent evaluators selected the studies, and a third one resolved the disagreements found. This procedure was performed in all phases of the present study. Experimental studies that evaluated Tskin in endurance sports were selected in this systematic review. Studies of systematic reviews, case studies, reviews with meta-analysis, and abstracts (studies without full text) were excluded. Studies with a publication date prior to the year 2000 were also excluded due to the low resolution of images from older cameras.

Data collection process

The following data were extracted from the studies: profile of the participants, sex, height, total body weight, percentage of fat, maximum oxygen consumption ($\dot{V}O_2\,max$), ROIs used in the assessment, Tskin, type of camera, and the outcome.

Methodological quality and bias's risk

Methodological quality and risk of bias were assessed using the Cochrane ACROBAT-NRSI scale. The instrument assesses seven domains: 1) confusion, 2) selection of study participants, 3) measurement of the intervention, 4) non-receipt of the assigned intervention, 5) losses, 6) measurement of the outcomes, 7) selective reporting of the outcomes. The first three are pre-intervention domains, and the other four are post-intervention domains. For each domain, the ratings "low", "moderate", "severe", "critical", and "no information" are assigned. The overall risk of bias in each study is the domain with the highest risk of bias (Sterne et al., 2016).

RESULTS

Figure 1 shows the flowchart of the studies included in the present study.

A total of 1128 studies were extracted from databases. The duplicated ones were excluded (421), and 16 were recovered by manual searches. From 723 studies to trial, 655 were excluded by not attending the inclusion criteria.

Table 1 shows the sample characteristic of 407 individuals who participated in these studies (380 male and 27 female). All studies presented the mean age, body weight, and height, except for Tanda (2016).

The ROIs were presented in Figure 2, where 24 different regions were used in the researchers' assessments. The most evaluated region in endurance sports was the thigh.

Table 2 presents the type of the camera, evaluation protocols, the camera position, and the outcomes of the analyzed

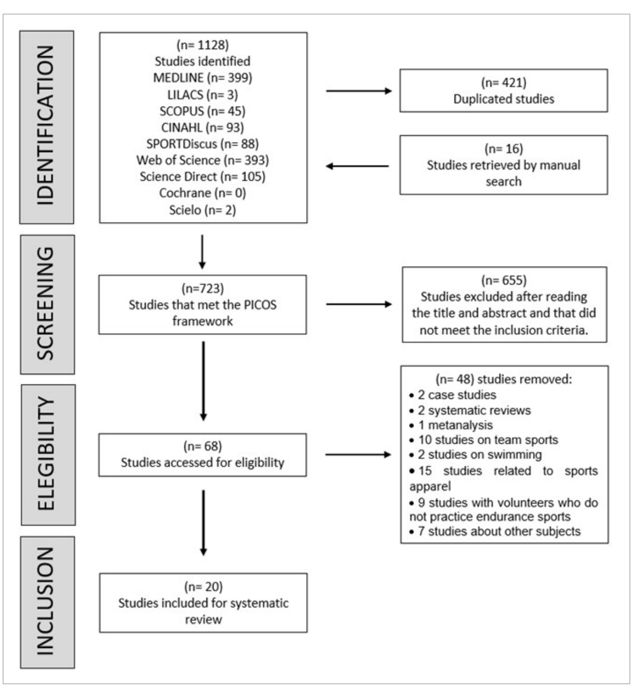


Figure 1. Flow diagram of the included studies in the systematic review.

studies. Table 3 presents the methodological quality and risk of bias analysis of the selected studies.

The main sources of bias in the present review were related to the pre-intervention and intervention phases. The lack of acclimatization of the volunteers before thermographic evaluations generated a confounding bias in sample results since the Tskin can be affected by movements prior to data collection, suggesting a moderate or severe risk in this domain (Rodriguez-Sanz et al., 2019; Balci, Basaran, & Colakoglu, 2016; Jensen et al., 2016; Bertucci et al., 2013; Smith & Havenith, 2011). Another bias observed in these studies was the sampling process, generating a selection bias, which was carried out for convenience (Tumilty, Adhia, Smoliga, & Gisselman, 2019; Balci et al., 2016). Some studies presented risks of bias during the intervention because they did not present information such as the position of the individuals, distance from the camera, the position of the camera, and characteristics of the equipment (Tumilty et al., 2019; Balci et al., 2016; Tanda, 2016; Smith & Havenith, 2011; Merla, Mattei, Di Donato, & Romani, 2010).

DISCUSSION

This systematic review identified 20 studies using IRT in endurance sports practice. It was organized by the patterns of Tskin assessment in endurance sports, such as ROI, equipment, protocols, and results.

The Tskin is influenced by the ambient temperature, and to avoid thermoregulatory effects, such as loss and gain of heat that can interfere in the IRT results, the ambient temperature must be between 18 and 25°C (Priego-Quesada, Salvador, & Cibrian, 2017). It can be seen that most of the included studies used this temperature range, with the exception of James, Richardson, Watt and Maxwell (2014), who used 31.9± 1°C. Other studies did not inform the temperature during the data collection (Jensen et al., 2016; Bertucci et al., 2013).

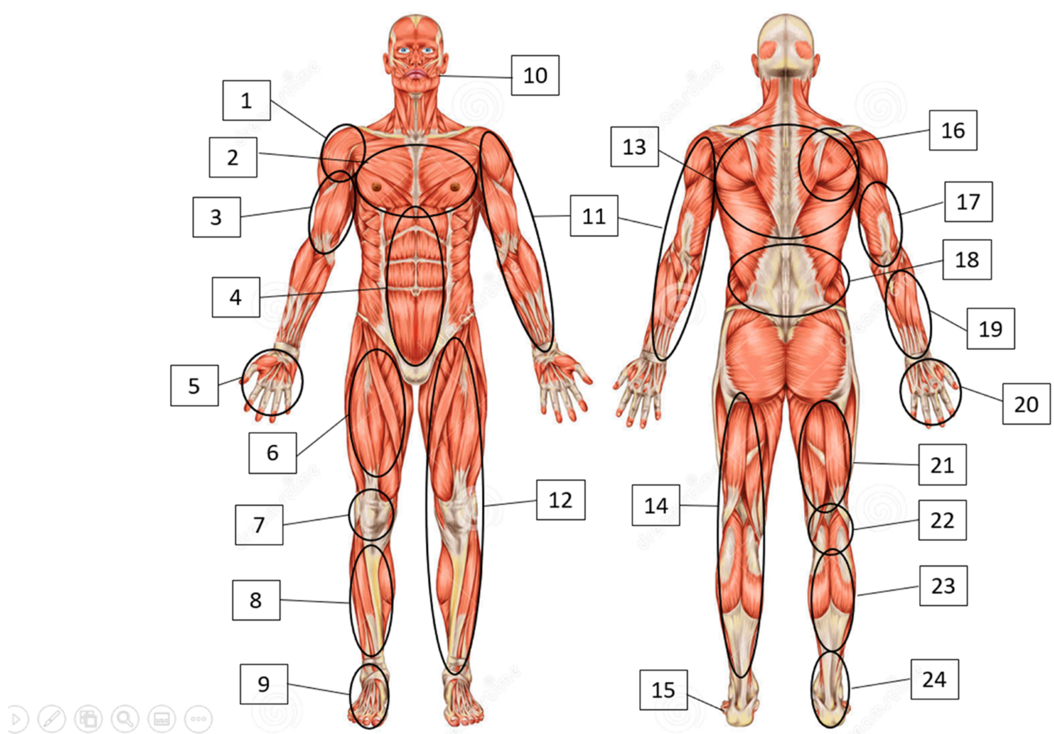
Another relevant element to observe is the relative humidity of the air since it influences the heat exchange between the body and the environment (Grinzato, 2010). There was no standardization since the relative humidity of the air presented in the studies varied from 19 to 69.9%. Two studies did not present it (Jensen et al., 2016; Bertucci et al., 2013). In humid environments, the effectiveness of heat loss decreases, and the humidity can condense in the body, resulting in heat gain that can alter the thermographic image captured (Johnson, 2010; Priego-Quesada et al., 2017).

In addition to the environmental variables, the acclimatization duration into the data collection room is also a

Table 1. Characteristics of the sample in the studies included in the systematic review.

Article	Study	Sample (n)	Age (years)	Weight (Kg)	Height (cm)	% Body fat	$\dot{V}O_2$ max (mL·min-1·kg)
1	Perez-Guarner et al., 2019	n= 17 (11 M and 6 F) Half marathon recreational runners	41± 6	66.5± 10	174± 0.10	14± 6.1	NI
2	Priego-Quesada et al., 2019	n= 10 (M) Recreational triathletes	40± 6	78± 12	176± 0,04	14± 5	63± 6
3	Tumilty et al., 2019	n= 29 (M) Competition runners	29.3± 5.8	65.5± 7.8	169.9± 6.2	NI	NI
4	Rodriguez-Sanz et al., 2019	n= 57 (M) Competition runners	42.82± 6.97	73.19± 8.13	173.68± 9.79	NI	NI
5	Priego-Quesada et al., 2017	n= 22 (17 M and 5 F) Runners	34± 5	72± 12.9	175.7± 7.3	NI	NI
6	Balci et al., 2016	n= 11 (M) Cycling, athletics and soccer athletes	22.2± 3.7	73.8± 6.9	181± 6.3	12.6± 4.2	54± 9.9
7	Jensen et al., 2016	n= 14 (13 M and 1 F) Recreational runners	28.1± 8.2	69,9 ± 7,5	177,6 ± 7,8	22,1 ± 1,7	NI
8	Ludwig et al., 2016	n= 7 (M) Elite cyclists	20.3± 1.8	70.14± 6.00	177± 0.03	8.64± 2.25	66.89± 4.55
9	Priego-Quesada et al., 2016a	n= 19 (M) Cyclists	29.5± 9.8	76.6± 9.2	179.2± 6.6	NI	NI
10	Priego-Quesada et al., 2016b	n= 16 (M) Cyclists that are club competitors	29± 10	77± 9	178.7± 6.5	NI	NI
11	Priego-Quesada et al., 2016c	n= 14 (M) Cyclists that are club competitors	29.9± 8.3	72.8± 10.6	175± 0.8	NI	NI
12	Tanda, 2016	n= 10 (M) Recreational runners	NI	NI	NI	NI	NI
13	Chudecka et al., 2015	n= 18 (M) Rowing club athletes	20.77± 1.78	82.33± 7.19	184.11± 4.56	NI	NI
		n= 16 (M) Handball players	22.54± 2.01	86.27± 7.17	187.25± 4.62	NI	NI
14	Priego-Quesada et al., 2015b	n= 44 (29 M and 15 F) Runners	29.3± 5.8	65.5± 7.8	169.9± 6.2	NI	NI
15	Priego-Quesada et al., 2015a	n= 14 (M) Healthy cyclists	28.9± 8.3	72.8± 10.6	175.8± 8	NI	NI
16	James et al., 2014	n= 14 (M) Recreational runners	38± 11	77.3± 7.1	179± 8	NI	57.3± 4.0
17	Abate et al., 2013	n= 40 (M) 20 trained runners (a) 20 untrained individuals (b)	26± 5.3 (a) 26.3± 4.9 (b)	70.5± 4.8 (a) 74.8± 5.1 (b)	175.2± 3.3 (a) 174.4± 5.3 (b)	22.9± 1.0 (a) 24.4± 1.4 (b)	NI
18	Bertucci et al., 2013	n= 2 (M) Competition cyclists	16± 0.0	63.0± 0.0	179± 0.0	10.4± 0.0	2.87± 0.20
19	Smith and Havenith, 2011	n= 9 (M) Elite and sub-elite runners	23± 3	73.8± 5.0	178.5± 4.1	10.9± 4.9	70.2± 13
		n= 9 (M) Elite and sub-elite runners	24± 5.7	73.6± 6.9	181.6± 4.3	11.8± 4.7	57.9± 11
20	Merla et al., 2010	n= 15 (M) University runners	25.2± 3.1	71.4± 4.2	175± 0.15	NI	NI

NI: not informed; kg: kilogram; cm: centimeter; $\dot{V}O_2max$: maximal oxygen consumption; M: male; F: female.



Studies	ROI Description	Study Objective
Perez-Guarner et al., 2019	4, 6, 7, 11, 12, 14, 18, 21 e 22	To associate the response to skin temperature and physiological stress after the half marathon.
Priego-Quesada et al., 2019	6, 7, 11, 12, 14, 21 e 22	To determine regional skin temperature in triathletes training with cumulative loads.
Tumilty et al., 2019	24	To determine skin temperature in the Achilles tendon in cross country athletes.
Rodriguez-Sanz et al., 2019	23	To evaluate how skin temperature may be related to the activation of the gastrocnemius muscle and, thus, to detect an association between the extensibility of the sural triceps and the pattern of skin temperature.
Priego-Quesada et al., 2017	15	To determine the relationship between foot eversion and the asymmetry of skin temperature in the sole of the foot.
Balci et al., 2016	2, 13	To examine changes in skinT between the maximal and submaximal cycling tests, at 60% of maximal oxygen consumption.
Jensen et al., 2016	Whole body	To estimate caloric expenditure in exercise using thermal images.
Ludwig et al., 2016	6	To evaluate the behavior of thigh skin temperature during exercise.
Priego-Quesada et al., 2016a	2, 4, 6, 7, 8, 9, 13, 18, 21, 22, 23 e 24.	To define the thermographic regions of interest (ROIs) in cycling as well as the effects of exercise on them.
Priego-Quesada et al., 2016b	2, 4, 6, 7, 8, 9, 13, 18, 21, 22, 23 e 24.	The effect of the bicycle seat height on skin temperature.
Priego-Quesada et al., 2016c	1, 4, 6, 7, 8, 9, 13, 18, 21, 22, 23 e 24.	To determine the influence of workload on cycling in relation to central temperature and different regions of the body.
Tanda, 2016	2, 4, 5, 6, 9, 10, 16, 17, 18, 19, 21, 23.	To assess the response to skin temperature in a running exercise.
Chudecka et al., 2015	2, 6, 11, 13	To evaluate the symmetry of muscle activity using infrared imagery in various exercises.
Priego-Quesada et al., 2015a	2, 4, 6, 12, 16, 23	To analyze the effects of running with and without compression stockings on skin temperature.
Priego-Quesada et al., 2015b	6, 7, 8, 9, 21, 22, 23	To compare infrared thermography and thermal contact sensors to measure skin temperature in indoor cycling at a controlled temperature.
James et al., 2014	2, 3, 6, 23.	To compare the reliability and validity of measurement tools through telemetry sensors and a thermal camera in runners.
Abate et al., 2013	2, 11	To compare skin thermal response to standardized heating in trained and untrained individuals.
Bertucci et al., 2013	6	To analyze the relationships between gross efficiency and skin temperature in cyclists' lower limbs.
Smith and Havenith, 2011	Whole body	To produce a detailed map of sweat patterns in athletes in mild exercise-induced hyperthermia.
Merla et al., 2010	2, 19	To analyze skin temperature changes in runners during graduated exercises.

Sup: superior; Inf: inferior; Post: posterior; Ant: anterior; Lat: lateral; From: frontal; ROI: region of interest.

Figure 2. Regions of interest.

Table 2. Results of the selected studies.

Studies	Type of camera software	Evaluation protocol		Clothing	Result
Perez-Guarner et al., 2019	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR	**Pre-race**: 48h, 24h; **Race**: 21Km; **Post-race**: 24h and 48h	**AT**: 10min, **TR**: 23.2± 0.1°C; **RHA**: 20± 1%, **TS**: < 0.05° C; **ES**: 0.98, **Ac**: 2%	Underwear	$_{skin}T$ in the posterior upper limb and anterior leg, after the half marathon. > $_{skin}T$ the day before the race for most ROIs.
Priego-Quesada et al., 2019	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR.	**Mom 1** – pre camp. **Mom 2** – 1st day camp. **Mom 3** – 2nd day camp. **Jump test**: 5 to 20 squat reps (warm-up)+ 3 maximum jumps with 30sec intervals.	**AT**: 10 min; **TR**: 18°C, **RHA**: 44%, 54% and 63% (pre, test 1 and 2); **TS**: 0.05°C, **ES**: 0.98; **Ac**: ± 2°C.	NI	> $_{skin}T$ after training in all ROIs. > $_{max\,skin}T$ in the posterior thigh, knee and posterior leg.
Tumilty et al., 2019	**C**: FLIR T450SC; **R**: 320x 240; **S**: FLIR Tools (FLIR Systems Inc).	A tests session of 30 min, for nine weeks.	**AT**: 15min; **TR**: 21.8± 0.46°C, **RHA**: 47.3± 8.1%; **Spectrum**: 7.5–13µm, **TS**: 0.05°C; **ES**: 0.95	NI	The IRT demonstrated high consistency and minimal variations in the Achilles tendon at rest during the 9 weeks.
Rodriguez-Sanz et al., 2019	**C**: FLIR/SC3000/ QWIP; **R**: 320x 240	5 images of the gastrocnemius taken before and after Ru at 8Km/h for 15min.	**TR**: 24.1± 1 C; **RHA**: 45%± 10%, **Spectrum**: 8–9 µm; **TS**: 0.02K (30°C).	NI	After the exercise, $_{skin}T$ was significantly warmer for the participants in all the variables for the gastrocnemius muscle.
Priego-Quesada et al., 2017	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR.	**Mom 1** (PT) – maximum effort for 5 min (400 m track). **Mom 2** – 10min warm-up, at 1% incline (60% MAS)+ 20min (80% MAS). **Measurement**: BT, IAT and 10 min after ending.	**AT**: 10min; **TR**: 22.9± 1.3°C, **RHA**: 44.4± 12.1%; **TS**: < 50mK (30°C), **Ac**: ± 1°C.	Shorts	Medial ROIs showed higher temperatures than lateral ROIs. Similar $_{skin}Ts$ were observed in ΔT and ΔT 10 of the hindfoot.
Balci et al., 2016	**C and S**: Testo 875–1 ThermaCA; **R**: 160x 120.	**Mom 1** – familiarization; **Mom 2** (max test) – 70 to 85% Max HR (90 rpm), (1x 4min)+ (3x 2min)+ (nx 1min until exhaustion). > 27 to 36W/stage. **Mom 3 (submaximal test)**: 4x 5min (until ventilatory threshold (50 to 60% Max HR Reserve> 27 to 36W at each stage).	**TR**: 21.3± 0.4°C; **RHA**: 64.5± 2.5%; **TS**: < 80mK (0.08°C); **ES**: 0.98.	Shorts,sneakers and socks	< $_{skin}T$ in the submaximal test until min 7.58± 1.03. After this, > $_{skin}T$. In the maximal test, < $_{skin}T$ during the whole period and it did not increase in any Mom.
Jensen et al., 2016	**C**: AXIS Q1922; **R**: 640x 480; **S**: AXIS Communications	**Mom 1** – warm-up 4min work 30sec recovery. Speed: 3, 5 and 7Km/h **Mom 2** –- 8, 10, 12, 14, 16, 18Km/h (Ru)	**TS**: < 100mK; **ES**: NI.	NI	> $_{skin}T$ with> Speed. It was not significant between 16 and 18km/h. The average values of the optical flow for all the 14 individuals demonstrated a strong correlation with oxygen uptake.
Ludwig et al., 2016	**C**: AVIO TVS700; **R**: 320x 240; **S**: thermal images analysis software.	**Mom 1** -- 10-min warm-up (100W); - Test- 100W+ 25W/min (80 to 90rpm). **Measurement**: BT, after warm-up, intra and IAT	**AT**: 10min; **TR**: 22–23° C, **RHA**: 50± 5%; **Spectrum**: 0.98, **TS**: NI; **ES**: NI.	NI	Base temperature was 32.50°C± 0.67. Post-exercise< $_{skin}T$ (30.87°C± 0.73). > $_{skin}T$ after release (3min) (32° C) and $_{skin}T$ after release (6min) reached 32.50° C.
Priego-Quesada et al., 2016a	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR.	**Mom 1 (PT)** – 5-minute warm-up (50W)+ 25 W/min until exhaustion (90± 3rpm). **Mom 2 (test)** – 3-min warm-up at 50 W (90± 2 rpm)+ 45 min at 50% of maximal power (90± 2rpm). **Measurement**: BT, IAT and 10min ΔT of Cy.	**AT**: 10min; **TR**: 23.7± 1.4° C; **RHA**: 45.1± 12.0% **ES**: 0.98, **Ac**: ± 2%.	Underwear	Previously, $_{skin}T$ was different among the three groups of ROIs. Regarding $_{skin}T$ variation, the anterior thigh group showed greater increase.

Continue...

Table 2. Continuation.

Studies	Type of camera software	Evaluation protocol		Clothing	Result
Priego-Quesada et al., 2016b	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR.	**Mom 1 (PT)** – 5-min warm-up at 50W+ load increase of 25W/min until exhaustion (90± 3rpm); **Mom 2 (test)**: 3-min warm-up at 50W (90± 2 rpm), followed by 45min at 50% of maximal power (90± 2rpm).	**AT**: 10min; **TR**: 23.4± 1.1 °C, 23.6± 1.2°C, 24.0± 1.2°C; **RHA**: 45.4± 12.5 %, 40.7± 11.3%, 50.8± 11.2%; **TS**: 0,05°C, **Ac**: ±2%.	Underwear	The knee flexion at 20° caused $>{}_{skin}T$ in the popliteal than at 40°. No differences in absolute temperatures among the three flexion angles in the other fifteen ROIs were found.
Priego-Quesada et al., 2016c	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR TRP FLIR.	**Mom 1 (PT)** - 5-min warm-up (50W)+ 25W/min until exhaustion (90± 3 rpm). **Mom 2 (test)**: 3-min warm-up (50W) (90± 2rpm)+ 45min at 35% and 50% of maximal power (90 ± 2 rpm). **Measurement**: BT, IAT and 10min after ending.	**AT**: 15min; **TR**: 21.8± 0.7°C, 21.2± 0.8°C; **RHA**: 39.4± 4.5%, 39.0± 4.9%; **TS**: 0.05°C, **ES**: NI; **Ac**: ± 2%.	Underwear	There are no differences in the absolute values of ${}_{skin}T$ between workloads (35% or 50%) in any ROI. In addition, Cy workload presented no effect on skin temperature variation in most ROIs.
Tanda, 2016	**C**: FLIR T335; **R**: 320x 240.	**Mom 1 (progressive load)**: 6km/h+ 1.5Km/h, each 5min, until 13.5km/h. **Mom 2 (constant load)**: 5min (6Km/h)+ 25min of Ru (12km/h), **Measurement**: each 5min.	**AT**: 10min, **TR**: 22± 0.3° C; **RHA**: 60± 2%, **TS**: 0.05°C; **ES**: 0.98.	T-shirt, shorts and sneakers	Progressive load – $<{}_{skin}T$. In constant exercise, $<{}_{skin}T$ reached a minimum value in the beginning, followed by an increase.
Chudecka et al., 2015	**C**: ThermaCAM SC500 camera; **R**: 320x 240; **S**: Agema Report.	**Mom 1 (Group 1)**: 30-min warm-up+ 2000m test (rowing). **Mom 2 (Group 2)**: 90min of resistance training (real game). **Measurement**: 20min BT and IAT.	**AT**: Group 1 – 30min; Group 2 – 20min **TR**: 25°C, **RHA**: 60%.	Shorts and sneakers	IAT, ${}_{skin}T$s were smaller than the initial ones. Group 1 – there was no asymmetry in ${}_{skin}T$. Group 2 – there was asymmetry both at the dominant and non-dominant sides.
Priego-Quesada et al., 2015b	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR.	**Mom 1 (PT):** 5min (max) 400m track. **Mom 2 (test)**: 10-min warm-up+ 20min (75% MAS)+ 3min at 60% and 1min at 5Km/h. **Measurement**: BT, IAT and 10min after it.	**AT**: 10min, **TR**: 23.7± 0.8°C; **RHA**: 48.8± 10.9%, **TS**: 0.05°C; **ES**: NI, **Ac**: ± 2%.	Undressed	Wearing socks led to $>{}_{skin}T$ in the regions of the body that were in contact with the garment. It also led to $>{}_{skin}T$ in some regions of the body that were not in contact with the garment.
Priego-Quesada et al., 2015a	**C**: FLIR E-60; **R**: 320x 240; **S**: TRP FLIR.	**Mom 1 (test):** 3-min warm-up at 50W (90rpm)+ 50% of maximal power at 90rpm± 3rpm. **Measurement**: BT, IAT and 10min after it.	**AT**: 15 min, **TR**: 21.2± 0.8° C **RHA**: 39.0± 4.9%, **TS**: < 0.05° C; **ES**: NI, **Ac**: ± 2%	Underwear	There was no difference between the measurement methods (IRT and thermopar sensor) in the pre-test but some differences IAT and after cool-down.
James et al., 2014	**C**: FLIR e40BX; **R**: 160x 120; **S**: Flir tools.	**Mom 1 (test):** 5min treadmill (8Km/h), followed by 5x 3 min (8 to 10Km/h) and increasing 1Km/h in each set.	**AT**: 40min, **TR**: 31.9± 1° C; **RHA**: 61± 8.9%, **Spectrum**: 7.5–13µm, **TS**: < 0.045°C, **ES**: 0.98; **Ac**: ± 2%.	NI	The reliability of the telemetry was acceptable during stress tests, while the IRT displayed some errors due to the sweat rate as a result of exposure to heat during the test.
Abate et al., 2013	**C**: FLIR SC3000; QWIP; **R**: 320x 240; **S**: TRP FLIR 2.9.	**Mom 1 (test)**: 1st Step: 0–5 min at 100W (60rpm); 2nd Step: 5–10min at 130W (60rpm); 3rd Step: 10–15 min at 160W (60rpm).	**AT**: 20 min, **TR**: 23 ± 1°C; **RHA**: 55± 10%, **Spectrum**: 8–9 µm, **TS**: 0.02K, **Lens**: 20°; **ES**: 0.98.	Shorts and sneakers	$>{}_{skin}T$ in untrained athletes than in trained athletes.

Continue...

Table 2. Continuation.

Studies	Type of camera software	Evaluation protocol		Clothing	Result
Bertucci et al., 2013	**C**: Cedip Titanium HD560M; **R**: 640× 512.	**Mom 1 (test):** 4-min warm-up+ 4min (100W)+ 40W each 4min. **Measurement** BT, during and immediately after ending.	**Wavelength**: 3.5 to 5 mm^ 0.25 mm.	NI	$_{skin}T$ at rest reached 31.41°C (before) and the same value afterwards. In individual 2, $_{skin}T$ reached 31.98°C (before) and + 0.9°C afterwards. During the test and 5 min after it, $_{skin}T$ reached the same temperature in individual 1 and it rose 0.9°C in individual 2 .
Smith and Havenith, 2011	**C**: Thermacam B2, FLIR; **R**: 160x 120	**Mom 2 (Ru test):** 1h (1% incline), 30min (55% $\dot{V}O_2max$)+ 30min (75% $\dot{V}O_2max$). **Measurement**: BT, before and after pad application and ΔT.	**TR**: 25.6± 0.4°C; **RHA**: 43.4± 7.6%.	Shorts and t-shirt	> Sweat rates in the central region (upper and middle) and lower back. < values (fingers, thumbs and palms). > sweat rates in the forehead compared to values in the chin and cheeks. > sweat rate in all regions (low and high intensity exercises) except for the feet and ankles.
Merla et al., 2010	**C**: FLIR SC3000 QWIP; **R**: 320x 240	**Mom 1:** 7x 2 min of TR, 10% of incline and speeds (3, 5, 7, 9, 11, 13, 15Km/h).	**AT**: 20min; **TR**: 23 to 24° C, **RHA**: 50± 5%, **Spectrum**: 8–9µm	NI	After warm-up, < $_{skin}T$, from stage 2 to 6, from 3° to 5°C and > $_{skin}T$ in recovery.

ROI: region of interest; C: camera; R: resolution; S: software; $_{skin}T$: skin temperature; AT: acclimatization time; TR: temperature in the room; RHA: relative humidity of air; TS: temperature sensitivity; TR: treadmill running; W: watts; BT: before the test; IAT: immediately after the test; ΔT: time after the test; ES: emissivity of skin; Ac: Accuracy; PT: pre-test; Te: test; PoT: post-test; Ru: running; Cy: cycling; NI: not informed; Pos: position; Dist: distance; H: height; Mom: moment; IRT: infrared thermography; Thermacam Researcher Pro 2.10 software, FLIR: TRP FLIR.

Table 3. Methodological quality and risk of bias of the selected studies.

Studies	Pre-intervention		During intervention	Post intervention				Risk
	1	2	3	4	5	6	7	
Perez-Guarner et al., 2019	Low	Low	Low	Low	Low	Low	Low	Low
Priego-Quesada et al., 2019	Low	Low	Low	Low	Low	Low	Low	Low
Tumilty et al., 2019	Low	Serious	Moderate	Low	Low	Low	Low	Serious
Rodriguez-Sanz et al., 2019	Moderate	Low	Low	Low	Low	Low	Low	Moderate
Priego-Quesada et al., 2017	Low	Low	Low	Low	Low	Low	Low	Low
Balci et al., 2016	Moderate	Serious	Moderate	Low	Low	Low	Low	Serious
Jensen et al., 2016	Moderate	Low	Low	Low	Low	Low	Low	Moderate
Ludwig et al., 2016	Low	Low	Low	Low	Low	Low	Low	Low
Priego-Quesada et al., 2016a	Low	Low	Low	Low	Low	Low	Low	Low
Priego-Quesada et al., 2016b	Low	Low	Low	Low	Low	Low	Low	Low
Priego-Quesada et al., 2016c	Low	Low	Low	Low	Low	Low	Low	Low
Tanda, 2016	Low	Low	Moderate	Low	Low	Low	Low	Moderate
Chudecka et al., 2015	Low	Low	Low	Low	Low	Low	Low	Low
Priego-Quesada et al., 2015b	Low	Low	Low	Low	Low	Low	Low	Low
Priego-Quesada et al., 2015a	Low	Low	Low	Low	Low	Low	Low	Low
James et al., 2014	Low	Low	Low	Low	Low	Low	Low	Low
Abate et al., 2013	Low	Low	Low	Low	Low	Low	Low	Low
Bertucci et al., 2013	Serious	Low	Serious	Low	Low	Low	Low	Serious
Smith and Havenith, 2011	Serious	Low	Moderate	Low	Low	Low	Low	Serious
Merla et al., 2010	Low	Low	Moderate	Low	Low	Low	Low	Moderate

1) confusion; 2) selection of study participants; 3) assessment of intervention; 4) non-receipt of assigned intervention; 5) losses; 6) assessment of outcomes; 7) selective report of outcomes.

considerable condition in IRT use (Marins et al., 2014). A great amplitude of acclimatization was found, varying from 10 minutes (eight studies) to 40 minutes (one work). Five studies did not report the use of acclimatization (Rodriguez-Sanz et al., 2019; Balci et al., 2016; Jensen et al., 2016; Bertucci et al., 2013; Smith & Havenith, 2011). However, there was a non-standardization about the clothing of subjects, where 6 studies standardized underwear (articles 1, 9, 10, 11, 14, and 15 according to Table 1), 1 using only shorts (5), 2 with shorts and sneakers (13 and 17), 1 with shorts and T-shirt (19), 1 with shorts, sneakers and socks (6), 1 with T-shirt, shorts and sneakers (12) and 8 studies did not inform the used clothing during the tests (articles 2, 3, 4, 7, 8, 16, 18, 20). These results reflected the importance of a standardization presented by Moreira et al. (2017) in the TISEM checklist. Since the type of clothing and acclimatization period influences the Tskin and affects the evaluated ROIs.

In general, there was an increase in Tskin after exercise (16 studies). However, one study observed a decrease in Tskin throughout the test (Balci et al., 2016). Priego-Quesada et al. (2016c) did not observe any variation in Tskin for the workload used. Tanda (2016) found that the individual's average Tskin decreases continuously during the progressive load exercise, whereas Chudecka, Lubkowska, Leznicka and Krupecki (2015), while measuring immediately after exercise, observed that the average Tskins were lower than the initial ones.

These results may be influenced by the lack of standardization of the period of the data collection. Ten studies (articles 1, 2, 3, 6, 10, 14, 16, 17, 19, and 20, according to Table 1) collected the infrared images always at the same time, respecting the subjects' circadian cycle. Only 1 study (9) reported that the data collections were carried out at different times, presenting it as a limitation of the research, and the other studies (4, 5, 7, 8, 11, 12, 13, 15, 18) did not control or did not report the data collection time. This fact could represent some bias since there is a correlation between the individual's circadian cycle with skin temperature (Moreira et al., 2017).

Most of the studies noticed a decrease in Tskin in the initial moments of physical activity that occurs due to the directing of blood flow to the active muscle generated by cutaneous vasoconstriction. This same behavior was described by Neves et al. (2015a) in their systematic review about the thermal response in different types of exercise. These authors reported that the decrease in Tskin during initial moments of physical activity was verified in different parts of the body. This behavior is due to skin blood adjustments that promote vasoconstriction of the blood vessels in inactive regions, offering greater blood flow to the muscular region under stimulation (Neves et al., 2015a). The performed tests in this systematic review ranged from a maximum test with incremental load to exhaustion (articles 1, 5, 6, 8, 9, 10, 11, 13, 14, and 18 according to Table 1) and tests with controlled load (2, 4, 7, 12, 15, 16, 17, 19 and 20) that reflects the greater vascularization at the active muscles.

After this initial decrease in Tskin, there is no standardized reaction. Several factors were pointed as responsible for the Tskin behavior in the subsequent minutes, but the duration and intensity of exercise were the main ones. These findings are in line with those reported by (Neves et al., 2015b).

The IRT has been consolidated as an excellent tool for evaluating Tskin and body thermoregulatory responses during exercise, however, caution is needed. The sensitivity of the skin to external agents such as ambient temperature, relative humidity, activities performed before data collection, and procedures during the evaluation can significantly affect the data collected.

It also must be pointed that the resolution of the cameras influences the results. Nonetheless, only 2 (articles 16 and 19) used equipment with resolution lower than 320x 240 pixels, besides, 7 studies (articles 1, 2, 6, 9, 12, 16, and 17) reported camera 0.98 emissivity and one study (3) reported 0.95 emissivity, below the value predicted at TISEM checklist.

The limitations of this review are related to IRT and the difficulty of controlling the factors that affect the thermal responses of these studies. The risks of bias related to selecting the samples and the lack of blinding evaluators in the outcome indicate that these results must be analyzed with caution.

CONCLUSION

Based on the presented studies, it could be concluded that the thermal assessment protocols for endurance sports respected the acclimatization time in 75% of the selected studies and that the thermal image collections were performed, predominantly, in three moments: before the test, immediately after the test and 10 minutes after the test. The used ROIs were mostly selected in responses of a specific muscle recruited in each modality, emphasizing lower limbs muscles.

Regarding the equipment used, FLIR cameras were used in 70% of the studies, with a minimum resolution of 320x 240 pixels. This aspect is very relevant since the results will always be associated with the software, quality, and technology of equipment, paying attention to the resolution (pixels), accuracy, and, mainly, to the data collection procedures (distance, camera angle, controlled stability, acclimatization, ambient temperature, and relative humidity.

Mostly, the Tskin behavior in endurance sports decreased in the initial moments of physical exercise and increased after exercise. After this initial decrease in temperature, the thermal response is mainly dependent on the duration and intensity of exercise. At constant speed exercise, the Tskin increased after a few minutes of the beginning.

However, there are still many questions about the effectiveness and precision of field assessments about thermal responses in endurance sports during exercise, which can be explored in future researches.

ACKNOWLEDGMENTS

Supported by Pró-Pesquisa CADESM/DECEx/Brazilian Army, EsEFEx and CCFEx.

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