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Effect of perspiration on skin temperature measurements by infrared thermography and contact thermometry during aerobic cycling

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HIGHLIGHTS

- Infrared thermography is suitable for measuring skin temperature in cycling tests.
- Thermal contact sensors interfered in the heat exchange process of the cyclists.
- Similar differences between methods were found in the instrumented and humans tests.
- Large ROIs presented lower temperatures than small ROIs after cycling.

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ABSTRACT

The aim of the present study was to compare infrared thermography and thermal contact sensors for measuring skin temperature during cycling in a moderate environment. Fourteen cyclists performed a 45-min cycling test at 50% of peak power output. Skin temperatures were simultaneously recorded by infrared thermography and thermal contact sensors before and immediately after cycling activity as well as after 10 min cooling-down, representing different skin wetness and blood perfusion states. Additionally, surface temperature during well controlled dry and wet heat exchange (avoiding thermoregulatory responses) using a hot plate system was assessed by infrared thermography and thermal contact sensors. In human trials, the inter-method correlation coefficient was high when measured before cycling ($r = 0.92$) whereas it was reduced immediately after the cycling ($r = 0.82$) and after the cooling-down phase ($r = 0.59$). Immediately after cycling, infrared thermography provided lower temperature values than thermal contact sensors whereas it presented higher temperatures after the cooling-down phase. Comparable results as in human trials were observed for hot plate tests in dry and wet states. Results support the application of infrared thermography for measuring skin temperature in exercise scenarios where perspiration does not form a water film.

1. Introduction

Skin surface temperature is one of the most important indicators for assessing the human thermal physiological state and the effectiveness of the thermoregulatory system [1,2]. Several applications of skin temperature measurement have been identified in research fields, such as clinical diagnosis [3,4], sports physiology [2,5,6,7], environmental building ergonomics [8], and clothing design with adapted thermal properties [9]. Two techniques are mostly applied to measure skin temperature: thermal contact sensors and infrared thermography.

Thermal contact sensors such as thermistors and thermocouples are widely used for skin temperature measurements. In case of wireless sensors, they provide test participants with great mobility as they do not interfere with their physical activity [10,11]. These sensors allow a continuous recording of the temperature in high-dynamic situations or below or in-between clothing

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layers [12]. Although the validity of wireless temperature sensors is accepted [11,13], determining temperature in just one single point can limit the understanding of human thermal response as the evaluated body part could be not properly represented. In addition, thermal interactions between sensor and environment can reduce the reliability of the measurement [11]. The attaching method to the skin (usually different types of clinical tapes) has been shown to affect the local heat transfer [14,15], and hence, the local thermal regulation and skin temperature [10,16,17].

Infrared thermography (IRT) has been successfully applied for many clinical purposes [4]. It has become more popular in the last years in sports physiology research due to its non-contact and non-invasive character [9,10,18,19]. It generally shows a high reproducibility [20,21], although some variation was detected in measurements between different days for distal body parts [21], probably due the large number of the factors that can affect the skin temperature [22]. By IRT is possible to analyze skin temperature distribution on surface of the entire body or some specific body regions of interest (ROI) [10]. Hence, IRT can provide a more representative temperature value of the body region than thermal contact sensors. However, in order to properly take infrared images of skin surface and to obtain correct values of temperature, some factors need to be controlled accurately. They mainly concern the surrounding environment [23,24], the participant preparation for the test [25,26], the use of the camera [27–29], and the IRT images post-processing protocol [30].

Besides, to get a correct value of skin temperature by quantifying the emitted radiation, the emissivity of the measured surface has to be known [31]. Scientific studies determining emissivity of the human skin have mostly agreed on the value of 0.98 [32–34]. Bernard et al. criticized that traditional clinical studies based on measuring skin temperature with IRT do not mention the emissivity they assumed for the skin [32]. Some disinfectants, gels or lotions that are commonly applied on the skin surface for medical or cosmetic treatments could affect its optical properties due to their lower emissivity [32,33]. Additionally, moistening of the skin surface due to perspiration may lead to difficulties in evaluating the temperature of the skin. Although sweat emissivity has not been determined, a coating of dew presented emissivity values as high as human skin [35], and hence, a low potential to modify skin surface emissivity could be expected. Nevertheless, Ammer suggested that a water coating on the skin due to "profuse" sweating might act as a filter for the emitted infrared radiation from the skin surface [36], even if the water layer is just a few microns as determined for other types of surfaces [35]. In such a case, IRT would be able only to measure the temperature of the outer surface of the sweat layer. This would produce a difference in temperature between wet and dry skin areas due to different heat transfer conditions. Removing the sweat or water from skin has been tried as a solution [37], however, temperature could increase as a consequence of touching or rubbing the skin surface. A sudden elimination of a heat sink such as evaporating sweat could lead to an increase in skin temperature. The application of IRT for measuring skin temperature in exercise could be limited by thermoregulatory perspiration. Nevertheless, to establish in which conditions IRT is providing reliable data remains still unclear.

Some attempts to validate IRT imaging by comparing with thermal contact sensors have been undertaken in the literature. Different studies observed higher temperature values measured by thermal sensors than by IRT at rest and during running exercise, and lower temperatures values for thermocouples compared to thermography measurements after exercise [10,16,38]. The authors suggested that the low agreement between methods could be mainly due to the fixation method of the thermal sensors on the skin and its effect on convective and evaporative heat loss in the region where the thermocouple was fixed.

Further research is necessary to understand the effect of sweat and the differences between IRT and thermal contact sensors in other exercises and conditions apart of those already studied. Moreover, most of the studies have not confirmed their results with instrumented tests.

The aim of this study was, therefore, to compare IRT and thermal contact sensors for measuring skin temperature in a moderate cycling scenario and subsequent cooling down phase. We assumed that our chosen cycling scenario does not cause 'profuse' sweating and thus no liquid water film able to hinder a reliable skin temperature measurement by IRT is formed. Additionally, small and large ROIs defined on IRT images were compared with the aim of assessing representativeness of punctual measurements for large areas. Finally, an instrumented test was conducted to be able to compare the methodologies in excluding human thermoregulatory processes when simulating heat exchange in dry and wet conditions.

2. Materials and methods

2.1. Human trials

2.1.1. Participants

Fourteen healthy male cyclists participated in the study (age: 28.9 ± 8.3 years, body mass: 72.8 ± 10.6 kg, height: 175.8 ± 8.0 cm, average cycling training: 162 ± 77 km/week, peak power output: 281.7 ± 38.3 W). All participants signed an Informed Consent Term in agreement with the Committee of Ethics in Research with Humans at the University of Valencia (approval number *H1384344515519*), and in agreement with the Declaration of Helsinki.

All participants were asked to abstain from drinking alcohol, coffee or other stimulants and from smoking at least 12 h before the test. They were refrained from sunbathing or being exposed to UV rays and from using sunscreen/sun blockers. They were recommended to eat a light meal at least two hours before the test. They were asked to avoid high-intensity or exhaustive exercise at least 24 h before the laboratory trials.

2.1.2. Test protocol

2.1.2.1. Pre-test. Participants completed a pre-test aimed at individualizing the cycling posture and the workload for a subsequent test. The cycling posture was determined using a kinematic 2D model by Kinescan/IBV system (*IBV, Valencia, Spain*). This posture was defined by maximum knee extension angle between 25° and 30°, horizontal saddle position defined by the plummet method [39], trunk flexion angle between 40° and 45° related to the transverse plane, and an arm extension angle related to the trunk between 75° and 90°. Participants underwent an incremental cycling test to exhaustion using a stationary cycle ergometer (*Cardgirus Medical, Bikemarc, Sabadell, Spain*). The incremental cycling test started with an initial workload of 50 W during 5 min and was followed by increments of 25 W/min until exhaustion as described elsewhere [40]. Pedaling cadence was controlled at 90 ± 3 rpm by visual feedback from the cycle ergometer head unit. Exhaustion was defined as the moment when cyclists were no longer capable of maintaining the pedaling frequency of 87 rpm. Peak power output (PO_{max}) was defined as the workload of the last stage completed with the requested pedaling rate.

2.1.2.2. Temperature collection test. The test consisted of the following phases (see Fig. 1):

1. Thermal adaptation phase (15 min): Standing in the laboratory. The investigator attached the skin temperature sensors within the first minutes of this phase.