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Application of Infrared Thermography in Sports Science

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Like an editor, this book is dedicated to all the authors of the different chapters who thanks to them, the book has been carried out.

More personally, to Rosa for her support and love during the edition and writing of the book, and to Marina for giving me strength and enthusiasm with her arrival.

Foreword

The use of thermography in sports may serve as an excellent example to illustrate the possibilities of the technological advances for application in the context of sports sciences. First known for its wide application in sciences like engineering and physics, thermal cameras are now more and more popular among sports scientists interested in better comprehend the exercise induced adaptations, which can lead to a new branch of application of thermography. At the same time, it shows us how challenging can be the use of new technologies, especially due to a lack of background of sports scientists to use thermography and to interpret the results. In a world where new knowledge is making available faster everyday, all those involved in sports science and medicine are requested to keep up to date, and it also depends on knowing methodological aspects of techniques used in the daily professional routine. Due to the increase in the interest of applying thermography, as shown in Chap. 1, literature was missing a book like this, in which we can follow a step-by-step guide since the basic background of thermography technique to the more complex applications of thermal measurements in the context of human motion.

Author's effort to keep the text clear and concise is recognized. Illustration and examples included in this book accomplished the goal of helping the proper understanding of the concepts included, and a relevant list of references may help the reader in finding further material to consult. At the same time that this book provides basic information for those not familiar with the thermography, more specific and complex aspects of the technique are discussed with examples that are useful to improve understanding of those who already have the thermography as part of their routine of work. The limitations and possibilities are clearly stated, which provide an unprecedented support for those who are currently using the technique, or plan to use it in the near future. These characteristics of the text ensure to the reader the necessary knowledge to identify the critical aspects necessary to the correct application of thermography in the study of human motion.

This book is organized into 12 chapters with each chapter beginning with an abstract and an introduction to the topic of discussion. Conclusion and perspectives are included, which help the reader to finish the reading with a clear idea of what are the next steps that could be important to development of the topic. Among the 12 very attractive chapters, unique is Chap. 11 that includes discussion on equestrian sports, showing the importance of considering not only thermography in the human body, but also in the interaction of the humans with the environment and other animals. Common to all the chapters is the uniqueness of the images and data presented, which helps to fully understand the concepts and more importantly contributes to a very clear presentation of authors' ideas.

This book has the potential to assume a leading position in the scientific literature related to thermography and will be a valuable addition to libraries of those who perform research on the topic of thermography, engage in clinical practice related to exercise and sports medicine or are decided to start using thermography in their practice. Furthermore, it is hoped that the information presented in this book will motivate you to seek additional knowledge in the use of thermography.

Uruguaiana, Brazil Felipe P. Carpes, Ph.D.

Preface

I remember my first experience using thermography. It was while working at the IBV (Institute of Biomechanics of Valencia). I was immersed in a R&D project about heating systems in sports clothing. One of my colleagues asked me to perform some thermal images for the report. The thermographic camera was quite big, like a video camera television. It was inside of a box and no one had used it, probably because no much researchers knew of its existence. I made the images, but I did not follow any protocol or really understand its camera operation. In my opinion, that first experience exemplifies the first experience that many people are having today in laboratories and research centres. It is true that the difference between today and my first experience is that now the cameras are more manageable, cheaper and better quality, and there are a greater number of studies in sports science. But in many cases, infrared thermography is coming to laboratories as a new instrument which is cheap and very interesting, and researchers begin to use it without having a significant knowledge in its methodology, in the physics of heat transfer and thermoregulation, or in the research studies performed in sports science to date. Therefore, many "first-timers" studies have clear errors in its design, methodology and interpretation. Probably, the easy use a priori of the infrared thermography camera is one of the main reasons of this problem. One of the objectives of this book is to be a guide for these first users of the infrared camera in sports science research centres, laboratories or sports centres.

After finishing my time at IBV, I started as a researcher at the University of Valencia. I was interested in a group that was beginning to conduct research about the applicability of the infrared thermography in sports science. This group was the Biophysics and Medical Physics Group of the Department of Physiology, led by professors Rosa Maria Cibrián and Rosario Salvador. On the other hand, I also decided to start working on the Research Group in Sport Biomechanics (GIBD) of the Department of Physical Education and Sports, led by professors Pedro Pérez-Soriano and Salvador Llana-Belloch. Thus, I began to conduct research using infrared thermography, first as a researcher within the Physiology M.Sc. programme, then as a staff researcher at funded projects and finally as a researcher within the Physiology Ph.D. programme. Some of the projects were biomechanical studies, and I implemented the analysis of the skin temperature with infrared thermography to assess interesting topics for me. Many of these studies are presented in the various chapters of this book. In each of these studies, I learned more about human thermoregulation during exercise and about the possible applicability of infrared thermography in sports science. In each of these studies, I would think that I was committing fewer errors. I hope this book will accelerate the learning process of future researchers using infrared thermography in sports science.

The aims of this book are as follows: (1) to show the applicability of infrared thermography in sports science, (2) to update the reader about the current knowledge in the different fields of application and (3) to provide the basic knowledge for the use and interpretation of the thermographic results. I expect that this book should provide a primary source for new students in the use of infrared thermography in sports science and hopefully an update for those who have been involved for a long time. This book not only is focused on sports researcher, but also it can be valuable for the sports technician in the medical and sports centres. Therefore, the aim of this text is to afford the reader the basic knowledge and the last updates for understanding the application of infrared thermography in sports science.

New findings are published in the last years about the dynamics of the skin temperature during exercise, the applicability of infrared thermography in sports science or the methodology of the technique. These findings, discussed in this book, provide fresh understanding on how it is possible to use infrared thermography in sports science, how thermoregulation influences sports performance, how injuries affect skin temperature and how is possible to use the temperature to evaluate garments and sports equipment, among others.

This book is organized into 12 chapters. Chapter 1 is a historical introduction of the application of infrared thermography in sports science. Chapters 2 and 3 are focused on providing the basic background and methodological knowledge to use correctly infrared thermography. From Chaps. 4 to 11, each chapter is focused on one field of application of infrared thermography in sports science. The final chapter aims to discuss the issues and possible developments of infrared thermography in sport science, in order to facilitate the future R&D. Each chapter begins with an introduction to the topic of discussion and ending with the conclusions of the chapter. Additionally, each of these chapters contains methodological aspects related specifically to the topic of discussion. An effort has been made to keep the text as concise and clear as possible yet as comprehensive as necessary.

I hope that this text will be a valuable addition to libraries of those who use infrared thermography in their sports research or in their professional field. Furthermore, it is hoped that this book will be useful to improve and orientate future studies and therefore improve the scientist's knowledge.

Valencia, Spain Jose Ignacio Priego Quesada

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Chapter 1
Introduction: Historical Perspective of Infrared Thermography and Its Application in Sport Science

Jose Ignacio Priego Quesada, Rosa María Cibrián Ortiz de Anda, Pedro Pérez-Soriano and Rosario Salvador Palmer

Abstract Within the various chapters of this book, the methodology and different applications of infrared thermography in sport science will be discussed. But what are the origins of infrared thermography? What has its development been like in sport science? The present introductory chapter of the book aims to show the historical developments of infrared thermography and, fundamentally, its application in sport science.

1.1 Introduction

Infrared thermography features and its applications are constantly evolving. In recent decades, the technique has seen significant development. Furthermore, approximately 20 years ago, the use of infrared thermography in sport science was uncommon. However, in recent years, many sport laboratories have acquired an infrared camera and have begun to undertake thermographic assessments. Knowledge of the evolution of thermography during the twentieth century in general, and in sports science in particular, can provide a perspective that helps in the present and future use of thermography.

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Infrared thermography has a large number of applications. As will be shown in the different chapters of this book, infrared thermography in sports science has applications in various fields: sports medicine, analysis of thermoregulation, clothing and sport equipment assessment, and so on. Outside the field of sports, thermography is used in a wide range of sectors. Infrared thermography is used in the military, policing and security work enabling night vision and surveillance. In electrical installations, nuclear power plants and other factories, it is used, for example, for the monitoring of electrical components. In medicine, it is used for the diagnosis of injuries and diseases. In firefighting, infrared cameras are used to locate people/animals in heavy smoke and for detecting hot spots in forest fires. Infrared imaging is used in building inspections to detect issues related to insulation and water leaks. There are also infrared satellites that measure the ocean temperatures continuously. Although this chapter will be focused as much as possible on sport and human assessment, we believe that it is necessary to use the chapter to show other different applications. Sometimes these applications may appear to be far from the field of sport science. However, they are necessary to know because they may contribute to ideas for future developments and research in sport science.

This chapter aims to provide a general overview of both the past and present of infrared thermography in sport science. However, in order to achieve this objective, it is first necessary to review the origins of infrared thermography and its applications in other fields. One of these fields, very close to sport science, is medicine, and the beginning of the use of infrared thermography in medicine will be reviewed.

1.2 Origins: Discovery of Infrared Radiation, the First Thermography and the Development of Infrared Sensors

Infrared thermography is an image technique used to record infrared radiation, which permits estimation of a body's surface temperature. Any object at a temperature above absolute zero (0 K or −273.15 °C) emits energy—electromagnetic radiation—depending on its temperature [1, 2]; for the ~ 37 °C of the human body, the emitted energy is in the infrared region of the electromagnetic spectrum (thermal radiation) [3, 4]. Aspects related to the physics principles of infrared thermography will be discussed in the Chap. 2.

Infrared radiation was discovered in 1800 by Sir Frederick William Herschel (born in 1738 in Hannover, Germany; died in 1822 in Slough, England), an English–German astronomer (Fig. 1.1). It is well known by all scientists working with thermography that William Herschel was the astronomer who discovered infrared radiation. However, there are some interesting facts that may be unfamiliar to some. Herschel was a professional musician and the director of an orchestra; he could be considered to be a professional musician and an amateur astronomer or scientist. Some of the discoveries he made in his dedication to astronomy was the observation of the planet Uranus in 1781, as well as the discovery in 1783 that the sun was not static as it had always previously been believed, but rather that the sun moves by dragging with it the planets of the solar system.

After learning a little more about William Herschel, we will discuss his discovery of infrared radiation. Herschel was interested in learning how much heat passed through the different colors by watching the sun filters. He set this objective because he observed that the amount of heat transmitted depended on color. Herschel thought that the colors themselves could filter out different amounts of heat, so he devised an original experiment to test his hypothesis. He directed sunlight trough a glass prim to create a visible spectrum (a rainbow, a division of the light in the different colors). He placed three mercury thermometers in the spectrum obtained by a glass prism in order to measure the heat emitted by each color [5] (Fig. 1.1). Herschel used three thermometers with blackened bulbs (to better absorb heat) and, for each color of the spectrum, placed one bulb in a visible color while the other two were placed beyond the spectrum as control samples. He found that the heat increased from the violet to the red color of the spectrum. However, he also observed that next to the red spectrum, when there was no light, the temperature was higher [5]. This experiment from Herschel was very important because it marked the first time that someone had demonstrated that there were types of energy that are invisible to our eyes. Herschel called this radiation "Calorific Rays", a name quite popular throughout the nineteenth century that finally was giving the modern term "infrared radiation".

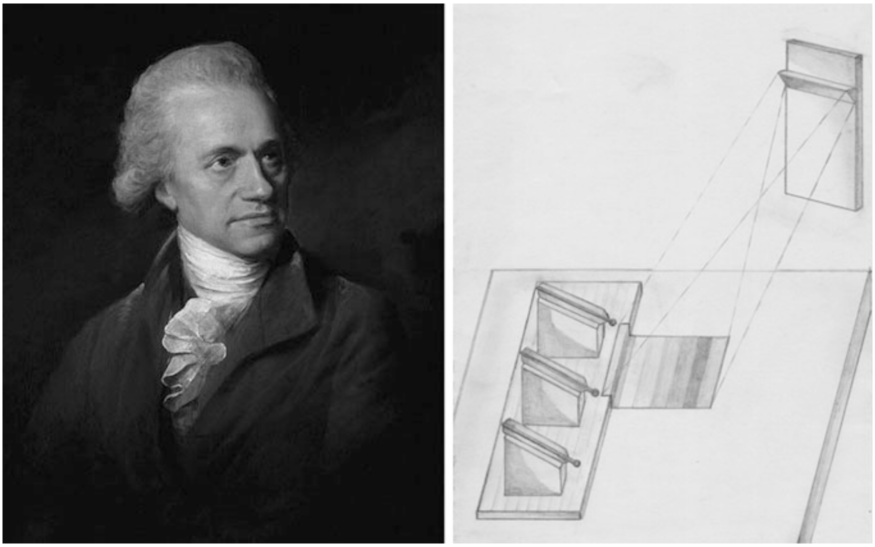

Fig. 1.1 William Herschel and the experiment in which he discovered infrared radiation

The following text is an extraction of the conclusion of the article in which Herschel explained the results of his experiment [5]:

> “To conclude, if we call light, those rays which illuminate objects, and radiant heat, those which heat bodies, it may be inquired, whether light be essentially different from radiant heat? In answer to which I would suggest, that we are not allowed, by the rules of philosophizing, to admit two different causes to explain certain effects, if they may be accounted for by one. A beam of radiant heat, emanating from the sun, consists of rays that are differently refrangible. The range of their extent, when dispersed by a prism, begins at violet-coloured light, where they are most, refracted, and have the least efficacy. We have traced these calorific rays throughout the whole extent of the prismatic spectrum; and found their power increasing while their refrangibility was lessened, as far as to the confines of red-coloured light. But their diminishing refrangibility, and increasing power, did not stop here; for we have pursued them a considerable way beyond the prismatic spectrum, into an invisible state, still exerting their increasing energy, with a decrease of refrangibility up to the maximum of their power; and have also traced them to that state where, though still less refracted, their energy, on account, we may suppose, of their now failing density, decreased pretty fast; after which, the invisible thermometrical spectrum, if I may so call it, soon vanished. If this be a true account of solar heat, for the support of which I appeal to my experiments, it remains only for us to admit, that such of the rays of the sun as have the refrangibility of those which are contained in the prismatic spectrum, by the construction of the organs of sight, are admitted, under the appearance of light and colours; and that the rest, being stopped in the coats and humours of the eye, act upon them, as they are known to do upon all the other parts of our body, by occasioning a sensation of heat.”

After the death of William Herschel, his son, John Frederick William Herschel (born in 1792 in Slough, England; died in 1871 in Collingwood, England), repeated the experiments of his father and made an image using solar radiation in 1840 [6]. This image was achieved by focusing solar radiation onto to a suspension of carbon particles in alcohol using a lens, a method known as evaporography [6]. He obtained an image that he called a “thermogram” (Fig. 1.2), a term that is still in use

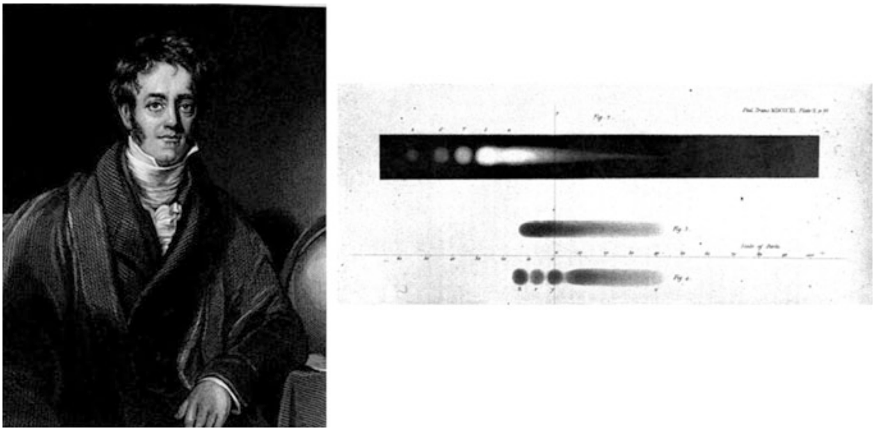

Fig. 1.2 John Herschel and the thermogram performed by him using the evaporography method. Figure modified from Ring [6]

today for the infrared thermography technique [6]. John Herschel was an important mathematician, astronomer, chemist, inventor and photographer (Fig. 1.2).

After John Herschel, some of the most important advances were related to the development of infrared detectors. Of course, the determination of the physical laws that explained the relationship between temperature and infrared radiation had great importance, but these laws will be explained in Chap. 2 of this book.

A bolometer is a device that measures electromagnetic radiation by the increase in the resistance of an electrical conductor. Samuel Pierpont Langley (born in 1834 in Roxbury, USA; died in 1906 in Aiken, USA) was the inventor of the balometer, originally called Langley's bolometer, in 1880 [2, 7]. The Langley's bolometer followed a continuous process of development over 20 years, increasing its sensitivity until 400 more times from the first prototype [7]. The last bolometer of Langley was able to detect the heat from a cow at a distance of $\sim$400 m [7]. It is considered that the invention of the balometer was relevant and important in the development of the posterior infrared cameras [2].

After the development of the bolometer, one of the most important steps was considered to be the development of the infrared photon detectors during the XX century [7]. The first infrared photoconductor was developed in 1917 [7], but the origins of the modern infrared detector technology are considered to have been developed during World War II [6, 7]. These detectors were developed at the end of World War II for use by snipers, to enable features such as rudimentary night vision [8]. These sensors involved the conversion of infrared radiation in visible light, due to the catchment of the electrons from near-infrared cathodes by the visible phosphors [8]. At the same time, another infrared detector was made from indium antimonide, and was mounted at the base of a small Dewar vessel to allow cooling with liquid nitrogen [6, 8]. This device had the limitation of requiring a constant supply of liquid nitrogen, which was impractical for battlefield, but not an important inconvenience in other fields such as the medicine [8].

1.3 Antecedents and Contemporaries: Infrared Thermography in Medicine and Other Applications

As was discussed in the previous section, modern infrared detectors were developed during World War II. The sensor was developed in this period for its military applications [2, 4, 9]. Its main use in the military field was, and remains, night vision. This utility is also highlighted when the objective is to detect people in dark environments and complex spaces. A clear example of this is border and maritime space supervision (Fig. 1.3).

After infrared thermography had been used in military applications, the technology was released for civilian uses [1, 9]. In 1934, human skin was described to be a good emitter of infrared radiation [10]. After that, infrared thermography started to be considered as a potential technique for skin temperature measurement and, then, as a possible way to enable diagnostic imaging in medical science [9]. In this regard,

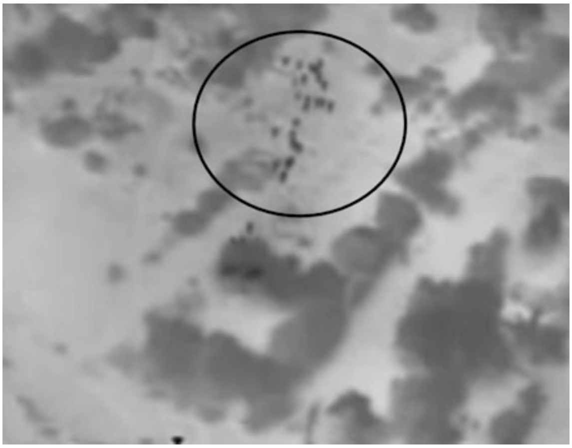

Fig. 1.3 Use of infrared camera in a helicopter as part of the border control of a country. Inside the *circle* it can see *small dots* that are people walking across the border during the night

one of the applications of infrared thermography that is very related to sport science was medicine, which is discussed below.

Although Vardasca and Simoes [2] reported that the first human thermographic image was done by Czerny in 1928 in Germany [11], Ring [6] described that the greatest advances of the techniques were performed in the 1940s and 1950s; these advances allowed a better quality of thermal images, but were very crude in comparison with modern thermographies (Fig. 1.4). Due to the advances of the

Fig. 1.4 Photography and thermography of one woman taken in 1949. Figure obtained from Ring [6]

technique in those years, infrared thermography is considered to have been used in medicine since the 1960s [1, 9, 12, 13]. It is considered that the first medical infrared images were taken at The Middlesex Hospital in London and The Royal National Hospital for Rheumatic Diseases in Bath, UK, between 1959 and 1961, using a prototype system called "Pyroscan" [6, 8]. This system represented an improvement in the quality of the image and "printed" the image line-by-line on electro-sensitive paper, but it took a lot of time to record each image (between 2 and 5 min) [6, 8].

The first applications of infrared thermography in medicine in that decade were the diagnosis of peripheral vascular diseases [14], its use in obstetrics and gynecology [15] and the detection of ischemic neuropathies [16], among others. A current overview of all the applications that infrared thermography has in medicine is provided by the interesting reviews performed by Ring and Ammer [17], and Lahiri and colleagues [9], both of which were published in 2012. These reviews extracted the following applications of infrared thermography in medicine: assessment of the thermoregulation, breast cancer detection, diagnosis of diabetic neuropathy and vascular disorder, fever screening, dental diagnosis, dermatological applications, blood pressure monitoring, diagnosis of rheumatic diseases, diagnosis of inflammatory arthritis, assessment of fibromyalgia, diagnosis of dry eye syndrome and ocular diseases, diagnosis of liver diseases, complementary test in the treatment of kidney, gynecology applications, and assessment of the psychological state [9, 17].

Of the above applications, cancer detection was one given a higher priority in the hope that it could be a valid screening technique [6]. In this sense, the earliest assessment of the temperature distribution of a breast cancer was reported by Ray Lawson in 1956 using the evaporograph system [18] (Fig. 1.5a). The author said in his publication: "*In its present state of development, the Evaporograph has a high resolution for objects having sudden or abrupt temperature changes, however slight (such as blacked-out cities at night), but where the temperature shows a smooth fall-off, the oil image lacks sensitivity, This remarkable device is quite capable of much future development*". Lawson, one year later, appreciated the potential of infrared thermography in the detection of breast cancer [19]. Different research groups have worked on this topic since the suggestion of Lawson in 1957 to the present day. Figure 1.5b shows a current breast thermography in order to illustrate how the technique has improved since Lawson's days. However, more research into infrared thermography is still required in order to improve its sensitivity and specificity in breast cancer screening and diagnosis [20].

In the beginning of infrared thermography's application in medicine, the technique was often discredited, mainly because the technology at the time was inadequate [22]. However, the improvement of the quality of the camera and the analysis of the thermal data over the years have led to the increasing use and efficiency of thermal imaging as a tool for diagnostic imaging procedures [22]. In this sense, infrared thermography was recognized as a feasible diagnostic and analytical tool by the American Medical Council in 1987 [3, 22]. After that, the application of infrared thermography in the assessment of skin temperature in medicine has been acknowledged and promoted by different worldwide thermographic associations, such as the American Academy of Medical Infrared Imaging, the International

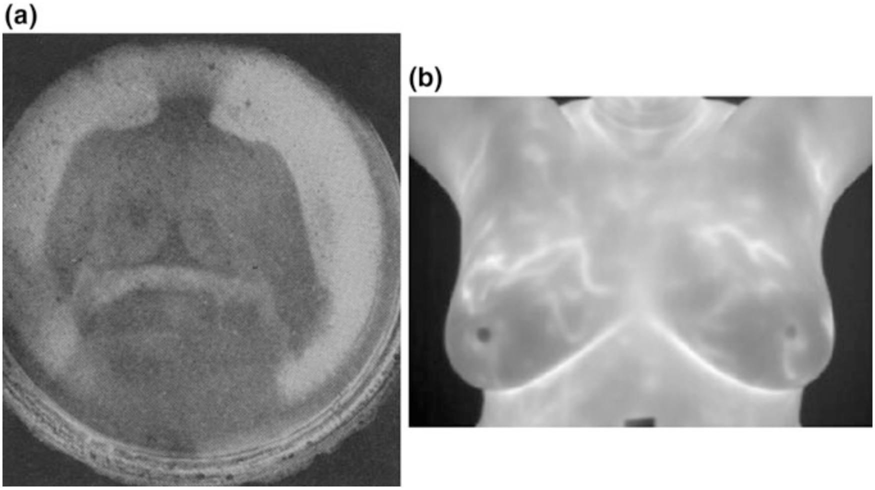

Fig. 1.5 Evolution of the thermal detection of breast cancer: **a** Evaporograph image in 1956 (figure obtained from Lawson [18]) and **b** current breast thermographies (figure obtained from Silva et al. [21])

Academy of Clinical Thermology, the International Thermographic Society, the European Association of Thermology, the Northern Norwegian Centre for Medical Thermography and the German Society of Thermography and Regulation Medicine [3, 23]. The main objective of these groups was and remains to develop reliable standardized methods and appropriate protocols for infrared thermography for clinical application [3].

Infrared thermography is used in other applications related to medicine (e.g., veterinary science) but also in other fields such, as engineering. Although these applications are further away from sport science, all of them are based on the assessment of heat transference. A superficial knowledge of its use can sometimes provides useful ideas for thermography assessment in sport science. For a review of a high number of applications of infrared thermography across different fields, the book of Vollmer and Möllmann [24] is recommended. In this chapter, some examples of representative and diverse applications are commented on below:

- **Veterinary science**. Infrared thermography has, in this area, a similar utility as in medicine. However, due to some characteristics, it has become very important in veterinary science. The difficulty of knowing the pain and the patient's condition without invasive techniques is higher in veterinary science than in medicine, and thus thermography is a low-cost, fast, efficient and simple method that allows knowledge of the status of the animal's injury [25] (Fig. 1.6). Additionally, the use of invasive methods produces anxiogenic responses in the animal that can affect the results [25]. Furthermore, it is considered that, in the veterinary field, thermography assessment can be useful to estimate the physiological state of

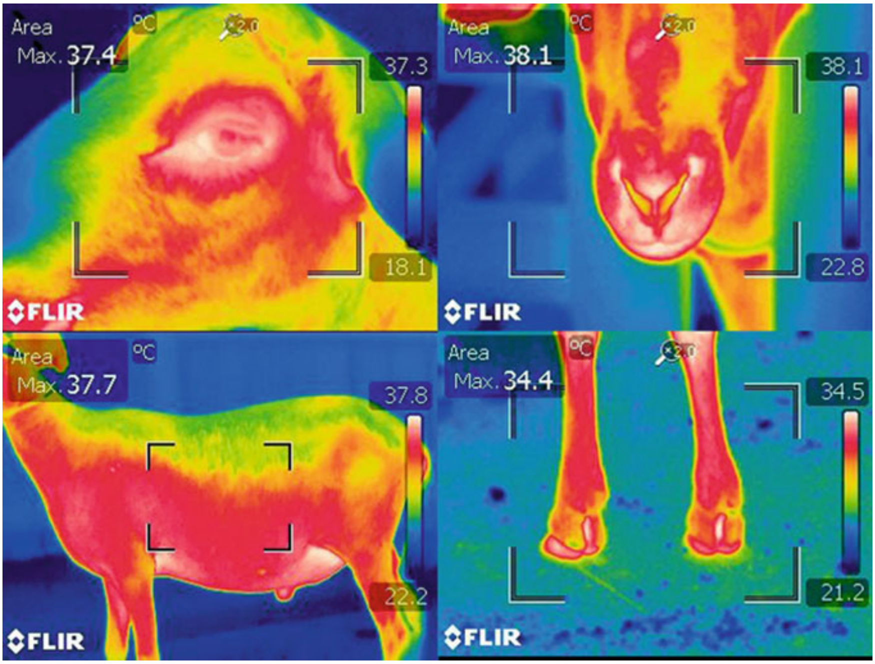

Fig. 1.6 Examples of thermographic images of sheep used to predict physiological stress. Figure obtained from McManus et al. [25]

animals in situations of stress, fertility, welfare, metabolism, health and disease detection [25].

- **Predictive maintenance of factories**. This application is widely used in electrical and nuclear facilities, and in different factories. This kind of application is particularly important when the factories need to work continuously without stoppages occurring in their activity due to breakdowns. In this context, infrared thermography helps routine inspections, where it is possible to visualize abnormalities in the components. This display of anomalies would be able to repair or replace components before they produce serious damage to the operation of the factory (Fig. 1.7). In addition, infrared thermography in this context allows the person to carry out inspection at a safe distance from hazardous components (e.g., those with high temperature or radioactivity) and to measure the temperature without contact. Another use in this field, especially in the petroleum chemical industry, is able to know the level of liquids and solids in the deposits [24].
- **Building Inspection**. Thermography is considered to be an excellent tool for diagnosing the state of buildings. Evaluation of insulation of different materials and/or the location of water leaks, and thus humidity, are specific uses of infrared thermography in this field (Fig. 1.8). One of the techniques used is the evaluation of heat flow, which consists of the generation of a thermal gradient

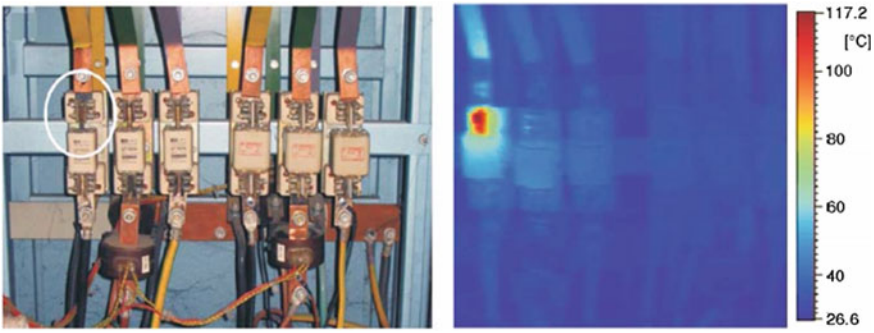

Fig. 1.7 Example of an electric fuse with a high temperature which can be a cause of breakdown. Figure obtained from Petar et al. [26]

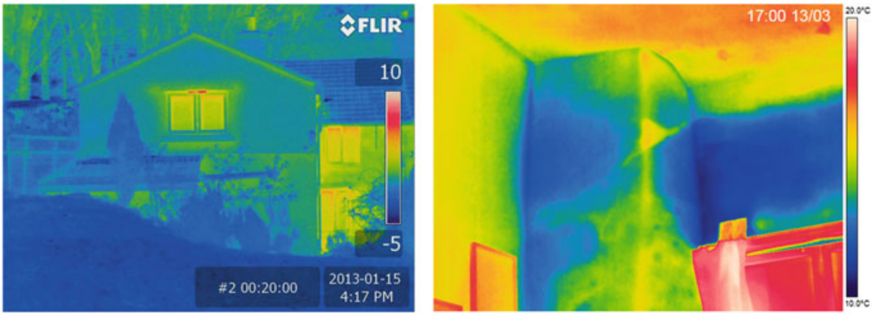

Fig. 1.8 Examples of thermographies in the building inspection. Figures obtained from Fox et al. [27]

between the inside and outside of the building. An example of this is that in the winter heaters heat the inside. Thus, through infrared thermography inspection from the outside of the building, it is possible to visualize whether there are hot areas. These hot areas are associated with heat transfer from inside to outside and therefore represent a problem with insulation in the walls or windows. If the whole outside surface of the building is a similar temperature, it means that the inside is properly isolated from the outside.

- **Gas detection industry**. Infrared cameras are able to visualize gases in a specific range of the infrared spectra (Chap. 2). Because of this, using the appropriate camera, it is possible to visualize specific gases such as the ethanol, carbon dioxide, propanol or sulfur hexafluoride, among others. This provides interesting applications of infrared thermography in the industry (Fig. 1.9). Two of the main applications are: (1) to check whether factories are not producing toxic gases or if the levels of the gases expelled are adequate; and (2) to check if there are leaks in the structures to store or transport gas.

Fig. 1.9 Thermography of the gas emission in a paper factory. Figure obtained from Sedlák et al. [28]

1.4 Infrared Thermography in Sport Science: Past and Present

In sport science, the studies using thermography started approximately 10 years after medicine. Furthermore, the first studies in sport science were related to its application in sport medicine.

The first study about thermography in sport science was in 1975 titled "Thermography in sport injuries and lesions of the locomotor system due to sport" by Keyl and Lenhart in the German journal *Fortschritte der Medizin* [29]. This study was written in German. In this study, the authors examined 82 patients and 50 athletes with different injuries. The main result of the study was the observation of hyperthermia in the injured area.

The next study in the field of the sport medicine was in February of 1977 and it was also performed by German authors and published in the German language. The study was titled "Skin-thermography with fluid crystals in orthopedics and sport-medicine" and it was performed by Lelik, Solymossy and Kézy and published in the journal *Zeitschrift für Orthopädie und Unfallchirurgie* [30]. Although we did not have the possibility to access to the paper, it is possible to show the English abstract: "*Thermography with fluid crystals is an effective diagnostic aid for the differentiation between bacterial and non-bacterial inflammation i.e. for the differential diagnosis between joint damage due to overloading and irritative arthrosis. Thermography enables us to assess severity and extent of the condition and to prove the success of treatment.*"

Just three months after the previous publication, the first study using infrared thermography in sport science in an English language by English authors was published in *The Journal of Physiology*. The study was titled "Skin temperature during running–a study using infra-red colour thermography." and the authors were Clark and Mullan [31]. This study was not oriented to the medical application as the previous studies were and its objective was to assess the validity of skin temperature

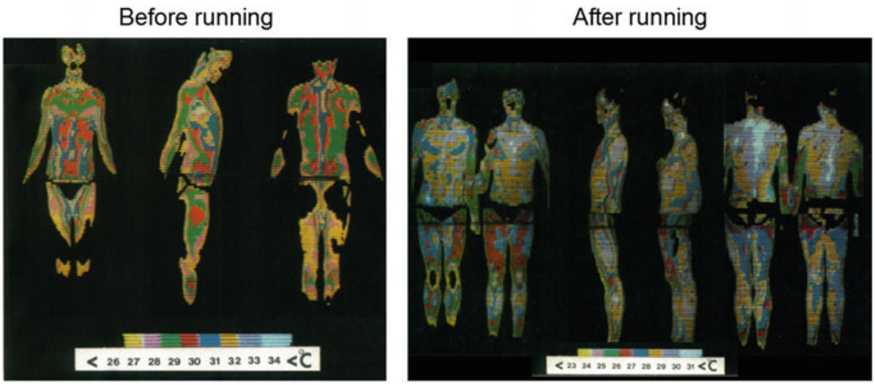

Fig. 1.10 Thermographies performed in the study of Clark et al. [31]

measurements under outdoor conditions. Two runners participated in the experiment. They ran for approximately 1 h and 15 min, one day in an outdoor track and another day in a climatic chamber. Measurements were performed before running and at 15-minute intervals during running, with an infrared thermography camera and thermocouples, in order to compare the data of both systems. In the climatic chamber, they also assessed the effect of the wind speed (no wind vs. 4.5 m s^{-1}). Figure 1.10 shows examples of thermographies obtained in this study. They obtained the following results [31]:

1. They analyzed the body temperature distribution before running. They described that the body temperature distribution depended on the following factors: body composition (i.e., body structures or regions with a higher proportion of fat presented lower temperatures), cutaneous blood flow (related to the warming of the hands), sweat rate evaporation, and muscle role (i.e., higher skin temperatures were recorded in the regions of the active muscles).
2. They observed a decrease in the skin temperature during running. Although this variation is different in each body region, an average value could be considered 5 °C. This decrease was associated with the sweat evaporation.
3. They observed in the images that emissivity of the skin was not influenced by the presence of sweat.
4. Similar temperatures before and during running were observed in the climatic chamber and in the outdoor track.
5. Infrared thermography could underestimate areas near the side of the body, due to the curvature of the body.
6. Thermography and thermocouples agreed, within 1.5 °C, on the mean skin temperature, but in specific regions could differ by 4 °C. The authors suggested that although thermography provides a more complete analysis, it is more expensive and consumes more time.

After observing the results and its discussion, it is interesting how this study from 1977 obtained results and discussed different topics that keep being topics of interest until the present such as the body temperature distribution [32–34], the effect of the sweat on skin emissivity [35, 36], and the differences between thermocouples and thermography [36–38], among others.

In order to know the trend of the number of publications performed in sport science using infrared thermography, we performed a search in two databases: PubMed (Medline) and ScienceDirect. The key words used in the online search included “thermography”, “thermovision” or “thermal imaging”, and “exercise” or “sport”. Boolean operators, ‘OR’ and ‘AND’ were used to combine within and between the search terms of the subject areas.

Figure 1.11 shows the result of this online search. This figure can be interpreted as showing a gradual increase in the number of publications. However, it is very easy to see that in recent years there has been a greater increase. In this sense, the number of publications in the first 5 years of this decade (2011–2015: 25 articles published in PubMed and 29 in ScienceDirect) is approximately the double that in the previous decade (2001–2010: 14 articles published in PubMed and 6 in ScienceDirect). The progressive increase in the number of studies using infrared thermography in sport science could be explained by some of the technique’s advantages. Infrared thermography is a non-invasive method that can be used at a distance, and does not interfere in human thermoregulation, unlike other skin measurement methods [3, 36, 37]. Additionally, this important increase in the number of studies in the last 5 years could be explained by the great decrease in the price of infrared cameras in the last years.

In addition to the number of publications, it is important to know in which fields or applications the studies were published, in order to understand which are the most important uses of infrared thermography in sports science. In this sense, we defined the following categories:

- Thermophysiology: thermography studies focused on the assessment of human thermoregulation. All the studies that assessed the effect of exercise on skin

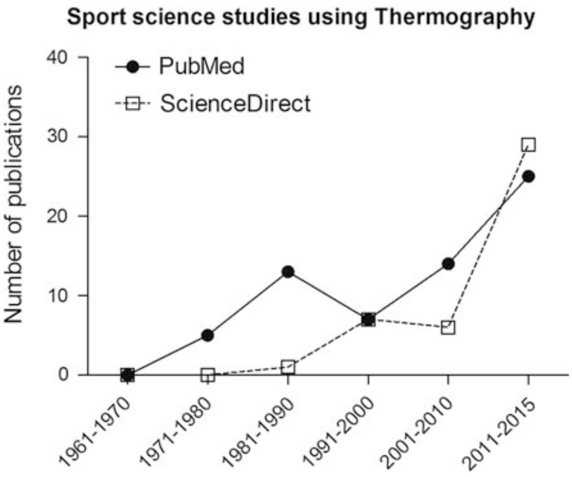

Fig. 1.11 Number of papers published in PubMed (Medline) and ScienceDirect using infrared thermography in sport science

temperature, the skin temperature distribution in relation to the sport or exercise, the differences in skin temperature between different groups (e.g., trained vs. untrained; young vs. old; woman vs. men), the effect of sport performance (e.g., VO_{2max} on skin temperature), and so on, were included in this category.

- Sports medicine: thermography studies related to the assessment of the effect of injury or disease in humans. In addition, this category included all studies that presented a clinical/medical perspective.
- Animals and Sport: thermography studies conducted with animals that are involved in an exercise or a sport. Papers with a clinical perspective involving animals were also included in this category. In this sense, this category would include the previous two categories, but with an animal focus.
- Clothing: thermography studies focused on the assessment of clothing in a specific sport or during exercise.
- Methodology/developments: studies that investigated the methodological aspects of the infrared thermography and developments of the technique. Studies that compared infrared thermography with other techniques (e.g., thermocouples), analysis of the data, determination of the regions of interest, guidelines, and so on, were included in this category.
- Reviews: reviews and overview papers about infrared thermography in sport science were included in this category.

Papers obtained in the online search in PubMed and ScienceDirect were categorized into the defined applications or fields (Fig. 1.12). During the approximately 40 years that infrared thermography has been used in sports science, the application that has been most used is sports medicine, representing 40% of the total number of papers. The second most commonly used application has been thermophysiology, with 31% of the total papers. In other application fields, the percentage of published

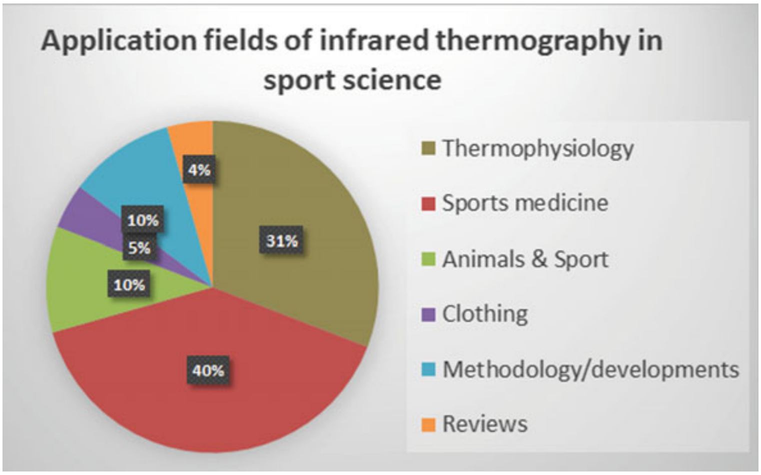

Fig. 1.12 Percentage of the papers published using infrared thermography in sport science in the different applications or fields

Table 1.1 The four most relevant publications using infrared thermography in sport science

Rank	Title	Authors and year	No of citations
1	An overview of recent application of medical infrared thermography in sports medicine in Austria [3]	Hildebrandt et al. (2010)	113
2	Skin temperature during running—a study using infra-red colour thermography [31]	Clark et al. (1977)	93
3	Dynamic thermography: analysis of hand temperature during exercise [39]	Zontak et al. (1998)	90
4	Thermal imaging of cutaneous temperature modifications in runners during graded exercise [40]	Merla et al. (2010)	88

Relevancy was defined by the number of citations (data from Google Scholar until July 2016)

articles is much smaller, but no less important, as will be shown in the different chapters of this book. It is important to comment that only papers that are focused on sports science were included in the methodology and review categories. If all studies related to infrared thermography in human assessment were included in these categories, without a focus on sport science, these sections would probably have the highest frequency of papers.

Finally, the four most relevant papers that used infrared thermography in sport science will be presented (Table 1.1). Relevancy was defined as the papers that have been cited the most times. These publications are discussed below.

The paper of Hildebrandt et al. [3] is an overview of the technological advances of infrared thermography in sports medicine and its technical requirements. The paper also presents the physical principles of the technique and a study of the intra-examiner reproducibility of knee temperature. It is very interesting that this article presents case studies to illustrate the clinical applicability and limitations of infrared thermography in sport medicine. The relevancy of this study could be explained because it is a complete publication about the application of the thermography in sport medicine, which shows the principles and the methodology of the technique, and which is very illustrative with different images and examples that demonstrate the potential use of infrared thermography in this field (Fig. 1.13).

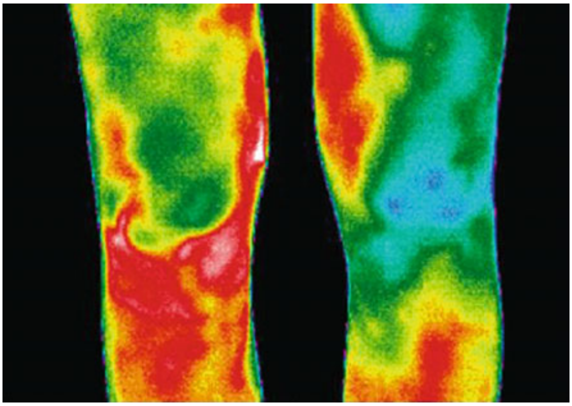

Fig. 1.13 Example of an injury (anterior cruciate ligament rupture in the right knee) presented in the article of Hildebrandt [3]

The second most relevant is the publication of Clark et al. [31], which was previously commented upon. Although the main limitation of this study is that it was performed with only two participants, its strengths are: (1) it was the first study written in English with infrared thermography in sport science; (2) the study deals with different aspects such as the effect of wind, the comparison of infrared thermography with thermocouples, or the comparison between performing exercise in a laboratory or outdoors; and (3) the study discusses many aspects, from the temperature distribution to the effect of the curvature of the body or sweat on thermal data.

Another relevant piece of research was the study performed by Zontak et al. [39]. In this research, they had the objective of characterizing skin temperature response to exercise (bicycle ergometry) using infrared thermography. They decided to measure the skin temperature of the hand in 10 participants because this area has a high skin blood innervation, resulting in a high variation of the skin temperature due to exercise (Fig. 1.14a). Two experimental protocols were assessed, an incremental workload and a stable workload. In the incremental workload, they observed a decrease in skin temperature during all exercise; and in the stable

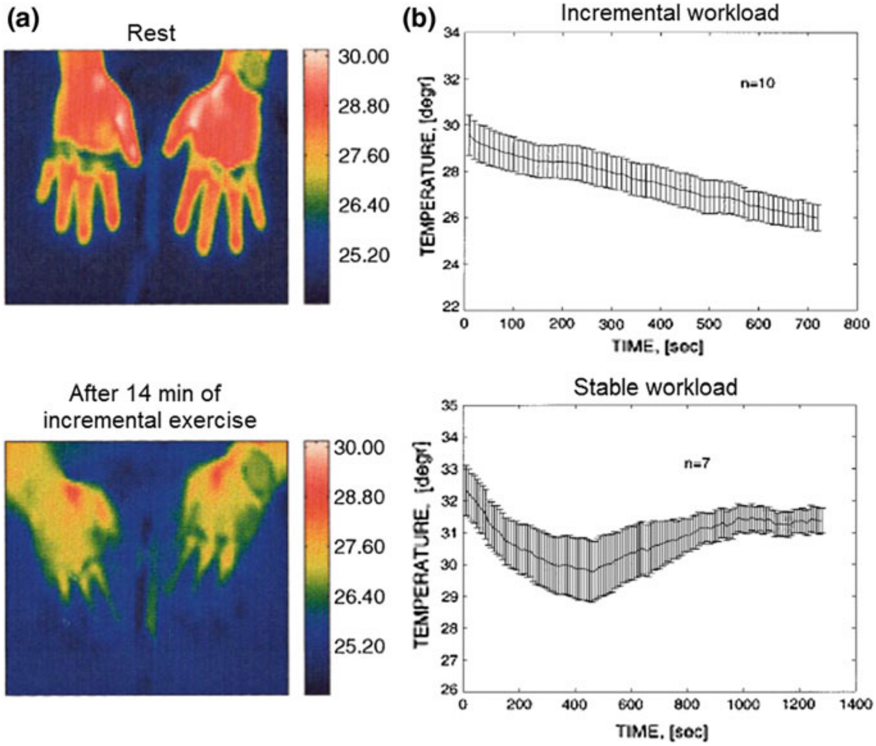

Fig. 1.14 **a** Example of hands thermographies from the study of Zontak et al. and **b** graphs of the skin temperature dynamics in their experiments. Figure adapted from the figures of Zontak et al. [39]

workload, a decrease in the skin temperature was first observed with a posterior increase in the skin temperature in the middle of the test (Fig. 1.14b). The authors suggested that these results depend on the vasodilator/vasoconstrictor balance of the skin blood flow, which depends mainly on the blood requirements for the active muscles and the skin (heat loss requirements). This study is very interesting and relevant due to this discussion regarding the effect of the vasodilation and vasoconstriction on skin temperature.

Finally, the fourth most cited study was the performed by Merla and colleagues in 2010, titled "Thermal Imaging of Cutaneous Temperature Modifications in Runners During Graded Exercise" [40]. In this study, they assessed the skin temperature dynamics of 15 participants during running an incremental test until maximal heart rate. They observed a decrease in skin temperature during all the incremental tests and an increment until basal values in the recovery (Fig. 1.15). Results were very similar to those of Zontak et al. [39]. The main strength of this study in relation to the previous studies was that they used the new generation of infrared thermography cameras, with a higher resolution and sensitivity. This study could probably be considered to be one of the first studies with this new generation of infrared cameras, which were more powerful and also cheaper. It may attract the attention of a lot of sport scientists in terms of the possibilities of the infrared camera in sport science.

These four studies provide a quick overview of the application of infrared thermography in sport science. More specifically, these studies are a good example of the two categories in sport science with the highest number of papers, as noted in Fig. 1.12: sport medicine and thermophysiology.

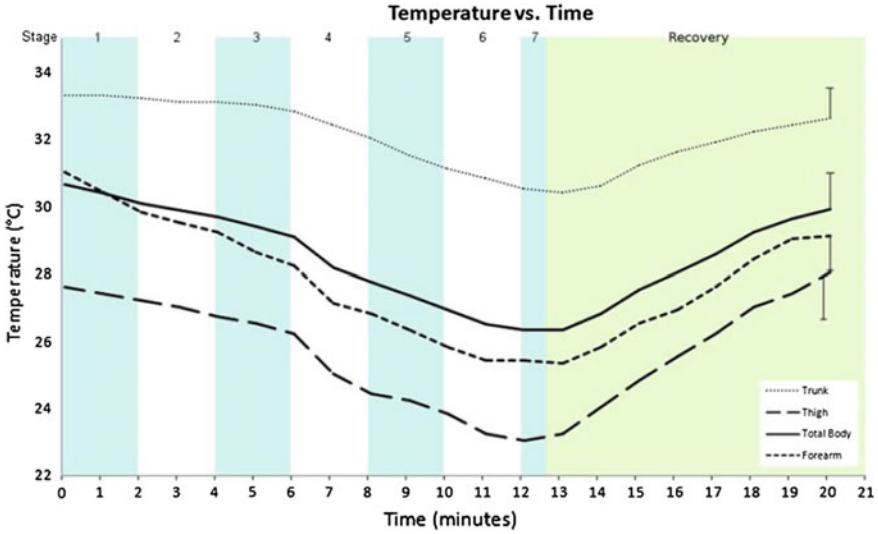

Fig. 1.15 Results obtained in the study of Merla et al. Figure obtained from Merla et al. [40]

Table 1.2 The five last publications using infrared thermography in sport science prior to the writing of this chapter (July 2016)

Date	Title	Authors	Journal
May 2016	The effect of noseband tightening on horses' behavior, eye temperature, and cardiac responses [41]	Fenner et al.	PloS One
May 2016	The influence of a menthol and ethanol soaked garment on human temperature regulation and perception during exercise and rest in warm, humid conditions [42]	Gillis et al.	Journal of Thermal Biology
June 2016	Estimation of energy expenditure during treadmill exercise via thermal imaging [43]	Jensen et al.	Medicine and Science in Sport and Exercise
July 2016	Long-term exercise training as a modulator of mammary cancer vascularization [44]	Faustino-Rocha et al.	Biomedicine and Pharmacotherapy
July 2016	Dynamics of thermographic skin temperature response during squat exercise at two different speeds [45]	Formenti et al.	Journal of Thermal Biology

However, a question may be called to mind after this review: what is the most recent application of infrared thermography in sports science? To investigate this, we decided to discuss the last 5 studies published in PubMed (Table 1.2).

The first study to comment on is the publication of Fenner and colleagues, titled "The Effect of Noseband Tightening on Horses' Behavior, Eye Temperature, and Cardiac Responses" [41]. In this study, the authors did not assess the horses in an exercise test, but rather the research was orientated to improve the equestrian sport. The aim of this study was to investigate the influence of noseband tightness on the physiology of horses. Infrared thermographic was used to measure eye temperature (Fig. 1.16). This analysis was performed because authors hypothesized that eye

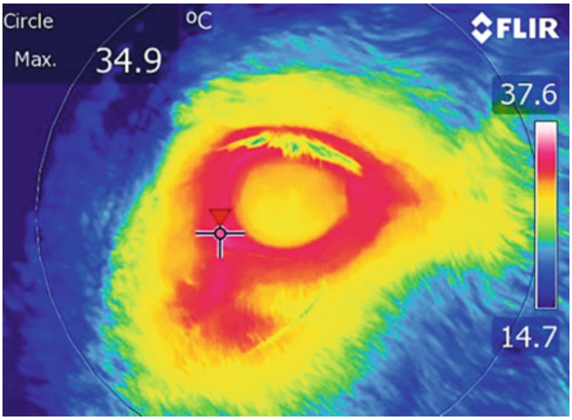

Fig. 1.16 Example of an infrared image of the eye region of the study of Fenner et al. [41]. They assessed the maximum temperature of a cross located in the medial posterior palpebral border of the lower eyelid and the lacrimal caruncle

temperature may be related to the stress response of the horse, due to the possible relationship between eye temperature, heart rate and heart rate variability. Although the authors did not find correlations between these parameters, when the noseband was tightest, eye temperature was recorded at the maximum value, accompanied by an increase in heart rate and a decrease in heat rate variability, suggesting that this condition produced an acute stress. Authors suggested that this no correlation could be explained because eye temperature and cardiac responses do not arise at exactly the same time.

In the second publication of the recent studies that we are discussing, Gillis et al. analyzed the effect of long sleeve breathable shirts soaked in menthol and ethanol solutions on rectal temperature, skin temperature, thermal perception and perceived exertion during rest and exercise [42]. To assess this effect, the researchers experimented three different conditions: exercise with dry shirt (control condition), exercise with shirt soaked by menthol and ethanol, and shirt soaked with water. Infrared thermography measured the temperature of the chest and the back. Garments soaked in menthol and ethanol presented the highest increment in rectal temperature, with the highest decrease in skin temperature recorded on the chest, and with the coolest perception. Authors suggested that the application of menthol could result in skin vasoconstriction and therefore decrease and increase skin temperature and heat storage (rectal temperature), respectively.

The third publication of the recent studies that we are discussing is the work of Jensen and colleagues titled “Estimation of Energy Expenditure during Treadmill Exercise via Thermal Imaging”. In this research, they validate the application of infrared thermography in the measurement of energy expenditure during running [43]. They used the parameter thermal optical flow. Thermal optical flow was defined as optical flow (movement of entities) estimated in succeeding thermal images. In total, 14 recreational runners ran for intervals of 4 min at different velocities when heart rate, oxygen uptake, optical flow and accelerations of body segments were measured continuously. The authors obtained a good accuracy of infrared thermography in the estimation of energy expenditure. One of the most interesting aspects of this study is that the authors did not use infrared thermography to measure skin temperature. They used the technique to obtain a high contrast between the body and the background in order to improve the estimation of the movement, and then the optical flow.

In July 2016, Faustino-Rocha et al. published a paper that aimed to assess the effect of long-term exercise training on the growth and vascularization of mammary tumors in a rat model [44]. Mammary tumors were assessed in the rats using different techniques (e.g., ultrasonography and contrast-enhanced ultrasound), and one of these techniques was infrared thermography. Infrared thermography was used in this study to evaluate the vascularization and the extension of necrotic areas of the tumors. Authors expected that higher vascularized tumors are associated with less extensive necrotic areas and, consequently, higher maximum, minimum and mean temperature, and lower thermal amplitude (difference between maximum and minimum temperature). Although, they did not obtain statistically significant differences in the parameters evaluated, they commented that the tendency of the data supported the previous idea.

Finally, in the most recent research of the present discussion, Formenti and colleagues analyzed the skin temperature response to two types of resistance exercises, modulating the amount of skin blood flow [45]. The rationale of this study was that low intensity resistance training with slow movement and tonic force generation has been shown to create blood flow restriction within muscles and therefore may affect skin blood flow and skin temperature response. With this hypothesis, the authors investigated the effect of two speeds of squat exercise execution (normal speed, 1 s eccentric/1 s concentric phase, 1 s; slow speed, 5 s eccentric/5 s concentric phase, 5 s) at 50% of 1 maximal repetition on skin temperature dynamics using infrared thermography, in 13 physically active males. Infrared thermography measured the skin temperature of the quadriceps. The results of the study showed that slow speed execution changed skin temperature more slowly during the exercise, whereas skin temperature variation was similar for the two exercises (Fig. 1.17). Authors commented that these data suggest that low speed exercise mimics a condition of blood flow restriction within the muscle, affecting skin blood flow and skin temperature dynamics.

It is interesting that in the discussion of the most relevant studies, these publications were mainly focused on sports medicine and thermophysiology. However, review of the most recent publications performed in sport science shows that there are new and different applications for infrared thermography, some of them related to other fields, such as the evaluation of additives in sports clothing [42], the assessment of equipment in equestrian sport [41], or the use of infrared thermography to measure other physiological variables such as energy expenditure [43].

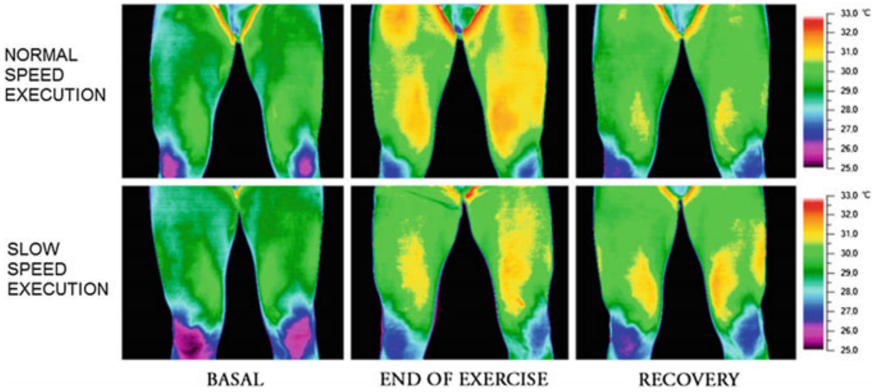

Fig. 1.17 Examples of thermographies of one of the participants of the study of Formenti et al. at the two speed executions of the squat exercise. Figure modified from Formenti et al. [45]

1.5 Conclusions

Infrared thermography began with the discovery of infrared radiation in 1800 by Sir William Herschel, the development of infrared sensors between 1880 and 1917, and, subsequently, the development of the infrared cameras in the 1940s and 1950s. After this, the infrared thermography started to be used in human assessment and, more specifically, in medicine. It is possible to consider the 1970s as being the beginning of infrared thermography in sport science; since then, the number of publications has been gradually increasing with the number of studies published between 2011 and 2015 double the amount published in the whole previous decade. Almost of the research has been performed in two kinds of applications: sport medicine and thermophysiology. However, infrared thermography presents other possible applications such as the sport clothing assessment/design, studies conducted with animals that are involved in the sport science field, or the improvement of the technique and the analysis for the sport science, among others. In conclusion, the application of infrared thermography in sport science presents an interesting past, an important present application, and a more promising future application.

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Chapter 2
Physics Principles of the Infrared Thermography and Human Thermoregulation

Jose Ignacio Priego Quesada, Rosario Salvador Palmer and Rosa María Cibrián Ortiz de Anda

Abstract Although it is easy to capture a thermal image with infrared thermography, it is necessary to have the basic knowledge about how it works and the physical laws relating to it, as well as the radiative characteristics of the different bodies, and how heat is transferred between space and bodies. This knowledge is essential to establishing a logical hypothesis, using the camera rigorously, and interpreting the thermal data correctly. The aim of this chapter is to present the basic physical principles of infrared thermography, heat transfer and human thermoregulation.

2.1 Introduction

In recent years, infrared thermography has become more popular in sport science due to several applications, such as injury prevention and screening [1], performance assessment [2, 3] and clothing assessment [4, 5].

Many researchers have recently begun studies using infrared thermography in sport science for different reasons. Firstly, it has many advantages: infrared thermography is non-invasive method that can be used at a distance and does not interfere in the human thermoregulation, unlike other skin measurement methods [1, 6, 7]. Secondly, it has great applicability as will be shown in the different chapters of this

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book. And finally, another important reason is the decrease in price of infrared cameras in recent years.

In the journal peer review process of different recent studies in sport science using infrared thermography performed by the authors of these chapters, we observed a high number of studies with important issues that make publication difficult. Most of these issues are related to methodological aspects or with the establishing logical reasoning to support the study hypotheses and to interpret the results. In this context, it is necessary that new users of infrared thermography in sport science have the necessary physics background to understand the technique, in order to avoid methodological issues. In addition, it is important to always remember that infrared thermography is commonly used to calculate surface temperatures, and, in this sense, knowledge about heat transference and thermophysiology is necessary to establish logical hypothesis and to correctly interpret the thermal results.

The present chapter will present the basic physical knowledge of infrared thermography, heat transference and thermoregulation. Because this book is not oriented towards physical scientists, all aspects will be discussed in a simple way in order to provide scientists in sports science the minimum knowledge necessary for its study. In order to study the physical aspects in more detail, it is therefore recommended to use other sources. Likewise, in this chapter, thermoregulatory aspects will be displayed briefly; in the following chapters, it will be explained in more detail and applied to the different topics.

2.2 Heat Transfer

First of all, it is important to define the concept of heat and temperature. **Heat** is energy in transit that passes from a warm body to a cold body and its unit is the joule (J). J/s or Watt are the common units used to measure heat flow per unit time. Hot body decreases its internal energy and cold body increases due to heat transfer.

On the other hand, the **temperature** is a measure of the internal energy of bodies. Temperature can be defined as the "measure" of the average kinetic energy of one body [8]. There are different scales for measuring temperature and the most well known are the degree Celsius, Kelvin and degree Fahrenheit. The degree Celsius is used by most countries in the world. The degree Fahrenheit is used in the Anglo-Saxon world and it can be changed to the Celsius scale using the following expression:

$$^{\circ}\mathrm{C} = (^{\circ}\mathrm{F} - 32) * \frac{5}{9} \tag{2.1}$$

Equation 2.1. Fahrenheit to Celsius formula

However, in the international system of units, the temperature is expressed using the Kelvin scale (K). This scale is called absolute, because it is not possible, by imperative of the laws of thermodynamics, to have bodies with lower values than the 0 K (−273.16 °C). The Kelvin scale is used in all aspects related to the physics of thermography.

The term heat, therefore, should be understood as heat transfer and only occurs when there is a temperature difference between two bodies. Therefore, the heat is always transferred following a gradient, from the hotter body to the cooler. This transference of energy is called **heat flow or heat flux** (Fig. 2.1). When two bodies are at the same temperature, they are in **thermal equilibrium** [9]. In addition, when one body has a constant temperature, it is considered that it is in a thermal equilibrium, and it could be a result of the environment being at the same temperature as the body, or because it has a constant supply of heat that keeps it at a constant temperature even though the environment is different (as in the case of the internal temperature of the human body, see Sect. 2.6).

Heat flow is an important concept in the human body. As will be shown in the next chapters, thermal gradient between the core and the skin, and between the skin and the environment are important in the rate of the heat transference. For example, the greater the difference between core temperature and skin temperature, the easier the transference from the core to the skin. Contrary, if both temperatures are similar, the heat dissipation from the core will be more costly [10]. Another example might be the temperature of the skin and the environment. In hot environments where the air temperature is similar or warmer than the skin, the body increases temperature due to the heat transfer by radiation.

Furthermore, the transference of heat is commonly explained by three mechanisms: conduction, convection and radiation. The three mechanisms are explained below, putting in context how they occur in the human body.

Conduction: heat transfer by the contact of two solid bodies at different temperatures. The amount of heat transferred by conduction is given by Fourier's law. This law states that the rate of heat conduction through a body per unit of cross-sectional area and is proportional to the temperature gradient existing in the body, being the proportionality constant material conductivity.

In the human body, the conduction transference is between the different structures of the body, and also between the human body and clothing. Regarding heat transference through the human body tissues, it is a slow process; in the limbs, it is mainly dependent on the temperature gradient between muscle and skin and the thermal conductivity of muscle [11]. For this reason, transference of heat by conduction is facilitated when the temperature gradient between the muscle and the skin is increased, occurring mainly by sweat evaporation during exercise or during

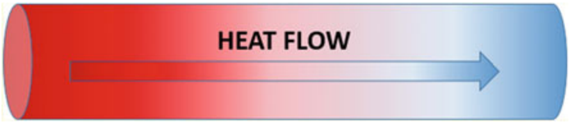

Fig. 2.1 Heat flow: the heat is transferred from the hotter side to the cooler

exercise in cold environments [10, 11]. Breathability and insulation properties of clothing will have an effect on this type of heat transfer. However, conduction heat loss is usually considered negligible unless the skin is in contact with highly conductive surfaces for a prolonged duration [12].

Convection: heat transfer by the contact of a solid body with a liquid or gaseous element. The convective heat exchange between the body and the fluid is given by the Newton's cooling law and depends on the temperature gradient and surface contact area of both, and the convective heat transfer coefficient (determined by the density, heat capacity, thermal conductivity and velocity of the fluid) [12].

In the human body, this convection could be explained by the heat dissipation via the blood flow; when blood flow through the core is heated, and that blood in turn heats the skin as it passes through. Convection also explains the effect of the wind on the skin. Wind convection also facilities sweat evaporation [12]. This heat transfer system is very important when the body is immersed in water. In this setting, it is considered that the 100% of heat loss occurs via convection due to the contact between the skin and the water. In the sports world, it is of interest to consider clothing insulation because it can promote or reduce convective heat loss.

Radiation: heat transferred by the body by emission of electromagnetic radiation. All of the objects with temperature above absolute zero (0 K or −273.16 °C) emit electromagnetic radiation according to the Stefan-Boltzmann law (see Sect. 2.4), which indicates that the energy radiated is proportional to the fourth power of its temperature. Furthermore, objects absorb electromagnetic energy emitted by the environment. Since the emission of energy implies a decrease in internal energy and thus the temperature of the object, if the object maintains a constant temperature (thermal equilibrium), it is because the energy emitted is compensated by the energy absorbed, but if a body is at a higher or lower temperature than the environment, the net radiative heat transfer is the difference between the absorbed and the emitted radiation.

Commonly, the human body emits more heat radiation than it absorbs, due to the environment being cooler. However, in close proximity to warm objects or hot environments (e.g.,a fire), this radiation is absorbed by the body, resulting in the body heating [9]. During outdoor exercise, the most common source of radiation is the sun [12].

Radiation is heat transfer that detects thermography, while conduction and convection are important for proper thermography protocols. Furthermore, conduction and convection could affect skin temperature, and therefore human radiation.

As will be shown in the following section, the emitted radiation of the human body temperature is in the range of infrared radiation in the electromagnetic spectrum and is called thermal radiation.

2.3 Electromagnetic Spectrum and Infrared Radiation

Electromagnetic radiation is a way of energy propagation through a vacuum or a material medium without mass transport. An electromagnetic wave can be defined as the propagation of the vibration of an electric field (E) and magnetic field (B), which together form an angle of 90° (Fig. 2.2). The propagation direction is perpendicular to both the plane of vibration of the electric field and the vibration of the magnetic field. It is therefore a transverse wave whose propagation velocity in the medium is $2.99792458 * 10^8$ m/s (this value is usually rounded to 3.10^8 m/s).

The quantities that characterize the electromagnetic waves are the amplitude of the electric field and the magnetic field and the frequency of the wave. The wavelength is the spatial period of the wave, which is the distance between two points with identical vibration state (from pulse to pulse), measured in meters, micrometers, nanometers, etc. (Fig. 2.2). Frequency is a quantity that measures the number of repetitions of the wave per unit time, and its unit is s^{-1} (Hz). Both quantities are related through the fundamental equation of wave motion:

$$\lambda = \frac{c}{f} \tag{2.2}$$

Equation 2.2. Relationship between the wavelength and the frequency. Where λ is the wavelength, C is the electromagnetic wave velocity (speed of light = 3.10^8 m/s) and f is the frequency

It can be observed in (2.2) that when the frequency increases, the wavelength decreases.

The **electromagnetic spectrum** comes from the concept that electromagnetic radiation has different characteristics depending on its wavelength and frequency. The electromagnetic spectrum is a representation of the frequency distribution of all the electromagnetic waves (Fig. 2.3). Regarding a body, the electromagnetic spectrum is all the electromagnetic radiation that is emitted (emission spectrum) or absorbed (absorption spectrum). The electromagnetic spectrum extends from the radiation of lower energy (or longer wavelength) such as the radio waves,

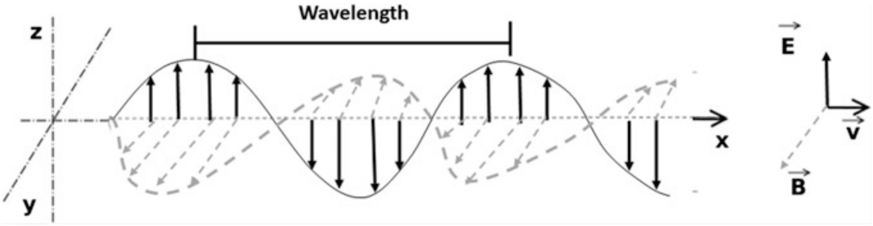

Fig. 2.2 Representation of an electromagnetic wave with the vibration of the electric field (E) and magnetic field (B) and the direction of the propagation of the wave

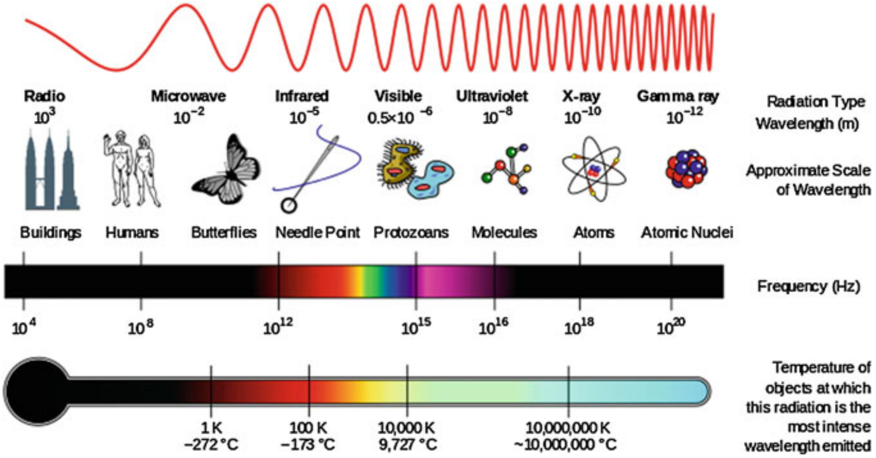

Fig. 2.3 Representation of the electromagnetic spectrum (Figure modified from the free media repository of Wikimedia Commons)

the microwaves, the infrared rays or the visible light, to electromagnetic radiation with higher energy (and shorter wavelength) such as ultraviolet light (UV), X rays and gamma rays. Most waves are commonly known to everyone. For example, X-rays are known for their medical applicability. UV is known due to the ozone hole, and it is widely known that a high incidence of this radiation increases the likelihood of skin cancer. The remaining types of radiation, such as the microwave or the radio waves, and its applications are also known to everyone.

For the different types of radiation, different imaging techniques were developed in the medical field, such as the X-ray or the arthroscopy [1] (Fig. 2.4).

The radiation that will be the focus of this chapter is infrared radiation. This radiation is also known as thermal radiation, and its wavelength range is from 760 nm to 1 mm. Infrared radiation is known as thermal radiation because there is a relationship between temperature and infrared radiation. In the Sect. 2.2, temperature was defined as the average kinetic energy of one body [8]. In other words, temperature is associated with the movement of the molecules in a body. More heat means more movement and more kinetic energy of the molecules. Changes in the speed and agitation of the molecules results in the emission of infrared radiation. Following on from this concept, it is easier to understand that all bodies that present a temperature above absolute zero (0 K or −273.15 °C) emit infrared radiation [9, 13]. This relationship between temperature or kinetic energy of one body and its emission of infrared radiation is the first concept to explain why it is possible to calculate temperatures from emitted infrared radiation. However, it is important to understand that bodies with very high temperature are capable to emit other radiations (visible and even UV), and bodies are heated during the absorption of their radiation. However, in bodies in which the temperature is close to the

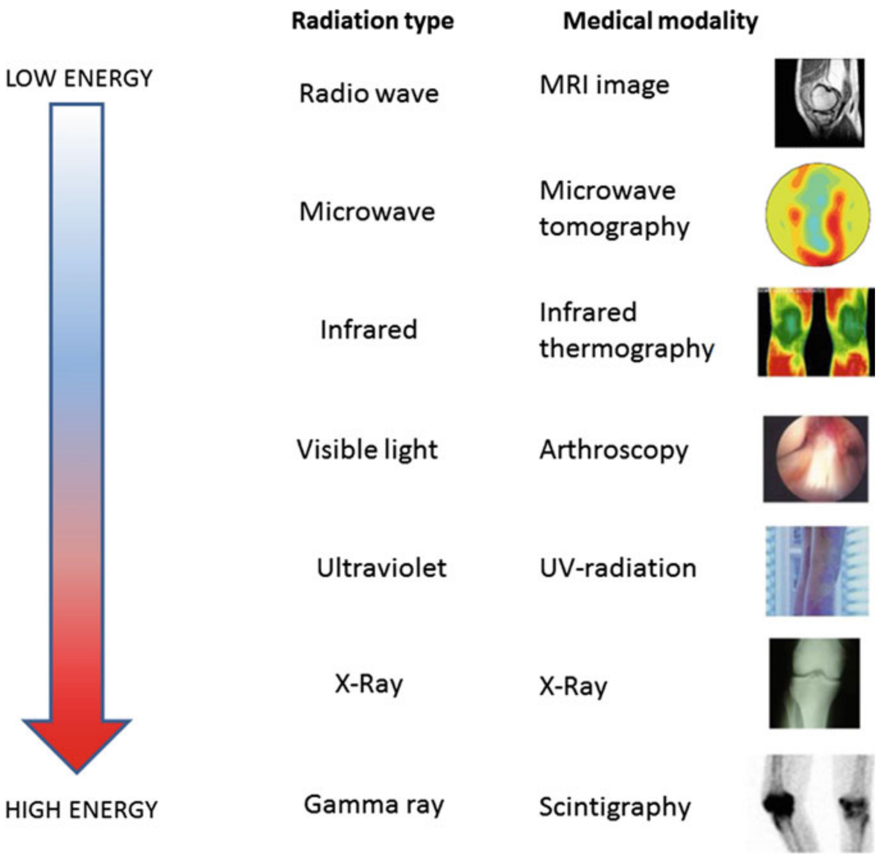

Fig. 2.4 Medical imaging techniques and its relation to the electromagnetic spectrum. Figure modified from Hildebrandt et al. [1]

environmental temperature, the energy radiated is from the infrared wavelength of the electromagnetic spectrum [14].

On the other hand, **infrared spectrum** is usually classified in three ranges: near infrared, middle infrared and far infrared (Fig. 2.5). The main reason for this division is because objects emit more radiation in one region than in others. For example, the human body emits most of its radiation in the far infrared [1, 15]. However, different gases and other elements can be transparent in the far infrared, but are visible in the near or middle infrared. Because of this, there are specific cameras to view specific wavelengths [16]. Cameras with detectors for the far infrared are the most commonly used because they register most bodies, including humans. However, there are also infrared cameras for the near or middle infrared, which are much more expensive but they are capable of visualizing specific gases (Fig. 2.6). There is also one specific window of the middle infrared (between 5 and

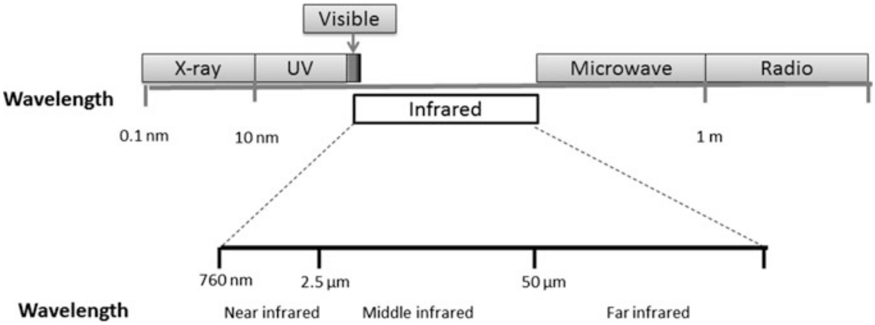

Fig. 2.5 Electromagnetic spectrum focusing on the infrared radiation spectrum

Fig. 2.6 Infrared camera with detector for visualizing the middle infrared, and then the CO_2 exhaled in the respiration. Figure extracted from Walther and Weimann [17]

7.5 µm) that is rarely used because it is the region where the atmosphere absorbs infrared radiation, and the air is opaque for infrared cameras [14].

Regarding infrared radiation, infrared thermography was developed. The next section is focused on the laws governing the emission of infrared radiation by bodies.

2.4 Physical Laws of Infrared Radiation

The physical laws of infrared radiation and its relationship to temperature are based on the theory of the **black body**. The concept of the black body was introduced by Gustav Kirchhoff in 1860. A black body is a theoretical object that absorb all incident electromagnetic radiation, and its absorption is equal to its emission. None of the incident radiation is reflected or passes through the black body. The black body also has a uniform surface and a uniform temperature. The black body is therefore an ideal perfect emitter of infrared radiation. Three properties are determined for the idea of the black body [16]:

1. A black body absorbs all the incident radiation, independently of the wavelength and the direction of the radiation.
2. For a specific temperature and wavelength, there is no surface that can emit more energy than a black body.
3. The emitted radiation of a black body depends on the wavelength; however, their radiance does not depend on the direction, it behaves like a Lambertian radiator (an object in which the surface has the same radiance from any angle).

Originally, black bodies were accomplished by a hollow sphere, covered internally with an insulate surface (in matte black) with a small aperture (Fig. 2.7a). This small aperture acts as a black body because any radiation that penetrates through it undergoes multiple reflections inside the cavity, each of which is partially absorbed, such that this radiation is completely extinguished before finding the exit. Currently, there are electronic instruments known as black body sources that are instruments with a stable and accurate temperature surface, with a high emissivity, that are configured with a specific temperature emission (Fig. 2.7b).

The quantity characterizing the emission of electromagnetic radiation by a body is called the **total emissive power**, E; that is, the energy emitted by unit of time and surface. Because this total emissive power is not equal in all the wavelengths (λ), there is also the **spectral emissive power**, E_{λ}, which is the energy emitted by unit of surface, time, and range of wavelength.

The graphical representation of the experimental curves corresponding to the spectral emissive power of the black body for each wavelength at different temperatures is shown in Fig. 2.8. This figure shows how the body emits radiation at different frequencies according to its temperature. For example, the sun, because it is at a temperature between 5000 and 6000 K, emits its radiation in the ultraviolet, visible and infrared spectrum; however, its emission peak is in the range of visible radiation (526 nm, corresponding to the green–yellow colors of the visible light). Humans visualize the sunlight as white because this emission peak is at the center

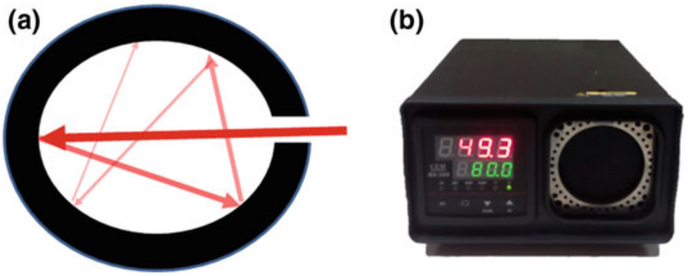

Fig. 2.7 **a** Origin of the concept of realization of a black body. **b** Current electronic black body source

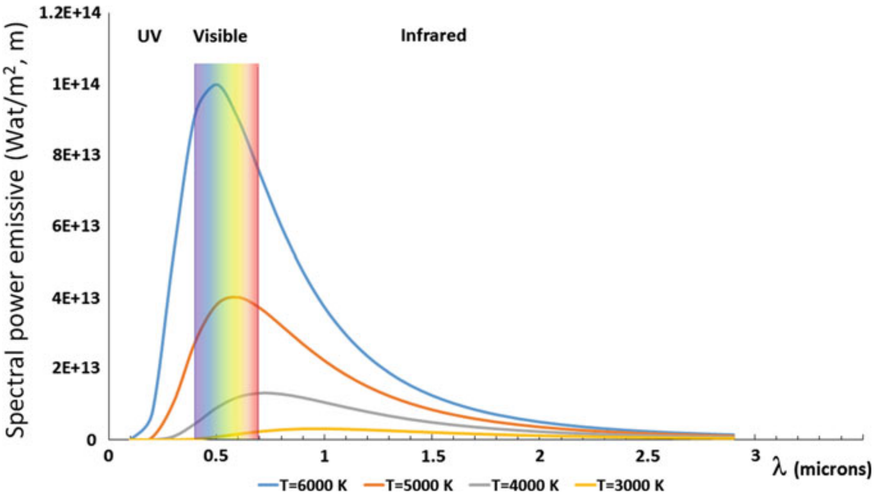

Fig. 2.8 Spectral emissive power of the black body for each wavelength at different temperatures

of the visible radiation [16]. As the temperature is lower in the bodies, its emission is higher in the infrared region. A black body with a temperature close to the room temperature does not emit in the visible range and emits all its radiations as infrared radiation [9] (Fig. 2.9). Thus, it is understood that for the 37 °C of human body (370 K), the maximum emitted energy is 9.3 μm, and therefore all its radiation is infrared radiation; more specifically, the 90% of the emitted infrared radiation is in the far infrared [1, 15] (Fig. 2.9).

Theoretical interpretation of these curves was not performed until 1900, representing a drastic change in the conception of physics, from classical physics to modern physics. It was also considered to be a pioneering result of modern physics and quantum theory [16]. However, the laws that govern the thermography were experimentally established much earlier.

Wien's displacement law was established by Wilhelm Wien in 1893. This physical law established that the wavelength of the peak of the blackbody radiation curve decreases as the body temperature is increased. The equation of Wien's displacement law is:

$$\lambda_{\max} = \frac{a}{T} \tag{2.3}$$

Equation 2.3. Wien's displacement law. Where λ_{max} is the wavelength of emission peak in meters, a is the Wien's displacement constant ($2.897 * 10^{-3}$ m K), and T is the absolute temperature in kelvin

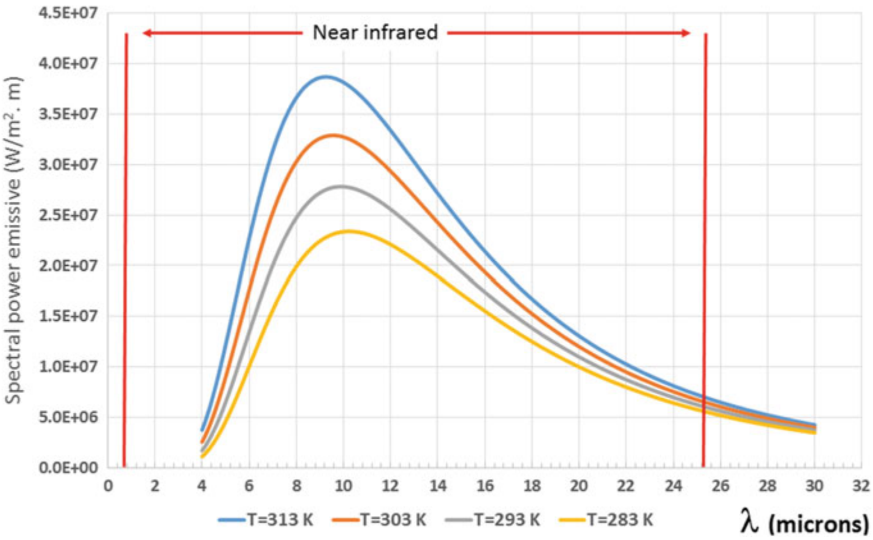

Fig. 2.9 Spectral emissive power of the black body at the following temperatures: 313 K (40 °C), 303 K (30°), 293 K (20°) and 283 K (10°). At these temperatures, all spectral emissive power is inside of the infrared spectrum

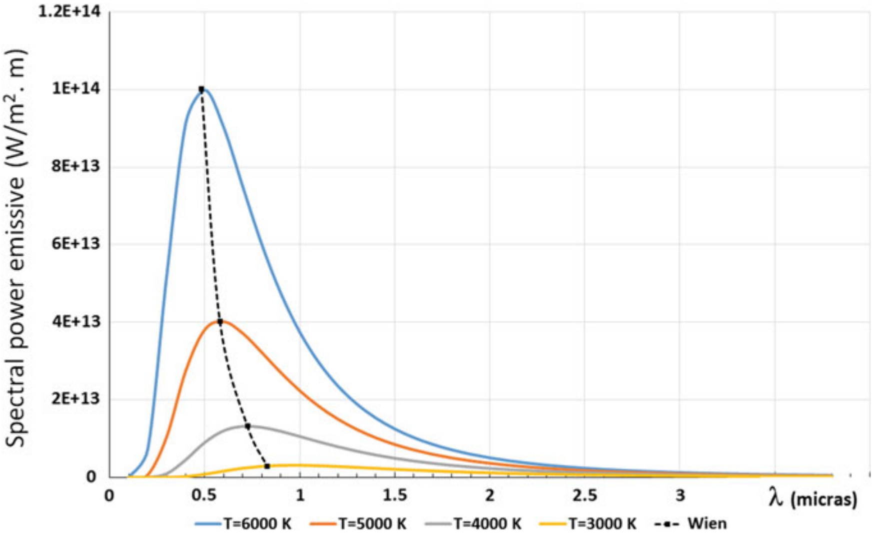

Fig. 2.10 Representation of Wien's displacement law at different temperatures of the black body

Representation of Wien's displacement law in the experimental curves corresponding to the spectral emissive power of the black body for each wavelength at different temperatures is shown in Fig. 2.10.

Stefan-Boltzmann's law was deduced by Josef Stefan in 1879 on the basis of experimental measurements made by John Tyndall and was derived from theoretical considerations by Ludwig Boltzmann in 1884. Stefan-Boltzmann's law expresses that the total emissive power or radiated energy from a black body is proportional to the fourth power of its absolute temperature:

$$E = \sigma * T^4 \tag{2.4}$$

Equation 2.4. Stefan-Boltzmann's law. Where E is the total emissive power (W/m^2), σ is the Stefan-Boltzmann's constant (5.67 * 10^{-8} W/m^{-2} K^{-4}), and T is the temperature in kelvin

Small changes in temperature resulted in big changes in the emissive power. This is really easy to see in the Stefan-Boltzmann's equation because the temperature is expressed as the fourth power. This relationship is very important because it explains how the calculation of the temperature from the emissive power is very sensitive and allows differentiation of areas at different temperatures, as they will have different emissive powers. It can be considered that the Stefan-Boltzmann's law is the fundamental law that governs infrared thermography.

For real surfaces, the Stefan-Boltzmann's equation is modified with the incorporation of emissivity (2.5). The concept of emissivity and also the consequence of this parameter in the equation will be explained in the next section. Most of the infrared cameras and radiation thermometers made the calculations using the modified Stefan-Boltzmann's equation [9].

$$E_0 = \varepsilon * \sigma * T^4 \tag{2.5}$$

Equation 2.5. Modified Stefan-Boltzmann's equation (2.4) where the value of the emissivity (ε) is incorporated

Wien's displacement law and Stefan-Boltzmann law were obtained experimentally before 1900. However, these laws were corroborated by the law established by Max Planck in 1900:

$$E_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{2.6}$$

Equation 2.6. Planck's law. Where E_λ(λ, T) is the spectral radiance as a function of temperature and wavelength, λ is the wavelength of emission in meters, T is the temperature in kelvin, h is the Planck constant (6.6256 * 10^{-34} Js), c is the speed of light in the medium (3 * 10^8 ms^{-1}), and k is the Boltzmann's constant (1.38054 * 10^{-23} W s K^{-1})

Integrating Planck's law for all frequencies leads to the Stefan-Boltzmann's law [13]. Applying the function maximum condition to the Plank equation (first derivative equal to zero) the Wien's displacement law is obtained.

After knowing the physical laws that explain the calculation of the temperature using infrared radiation, it is important to understand the radiative characteristics of one body in terms of its absorptivity, emissivity, reflectivity and transmissivity.

2.5 Radiative Characteristics of the Bodies

Infrared radiation has a behavior very similar to visible radiation. For this reason, its propagation can be described in the same way as the geometric optics [16]. In homogeneous materials, infrared radiation propagates in a straight line as if it were rays. Furthermore, the geometrical properties of reflection and refraction are also applied to infrared radiation, so that geometrical characteristics of the surfaces, such as uniform or roughened surfaces, have an effect on the emission and absorption of infrared radiation [16]. In the visualization of the human body, these considerations are important in understanding why the delimitation of the body in the image presents a lower estimation of the temperature. In this sense, the loss of infrared radiation in the outline of a body was identified as an important source of error (Fig. 2.11) [18–20].

Infrared radiation that arrives on a body can be absorbed, reflected or can pass through the body, depending on its physical characteristics (Fig. 2.12). These characteristics define the behavior of one body in relation to the infrared spectrum:

- Absorptivity (α): capacity of one body to absorb infrared radiation.
- Emissivity (ε): capacity of one body to emit its own infrared radiation. This parameter corresponds to the absorptivity ($\alpha = \varepsilon$).
- Reflectivity (ρ): capacity of one body to reflect the infrared radiation that comes from the environment.
- Transmissivity (τ): capacity of one body to let pass through it the radiation. If radiation is not transmitted through the body, this body it is therefore called opaque.

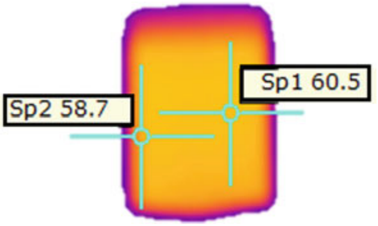

Fig. 2.11 Effect of curvature in the infrared emission and the temperature calculation of an object with a homogenous temperature surface

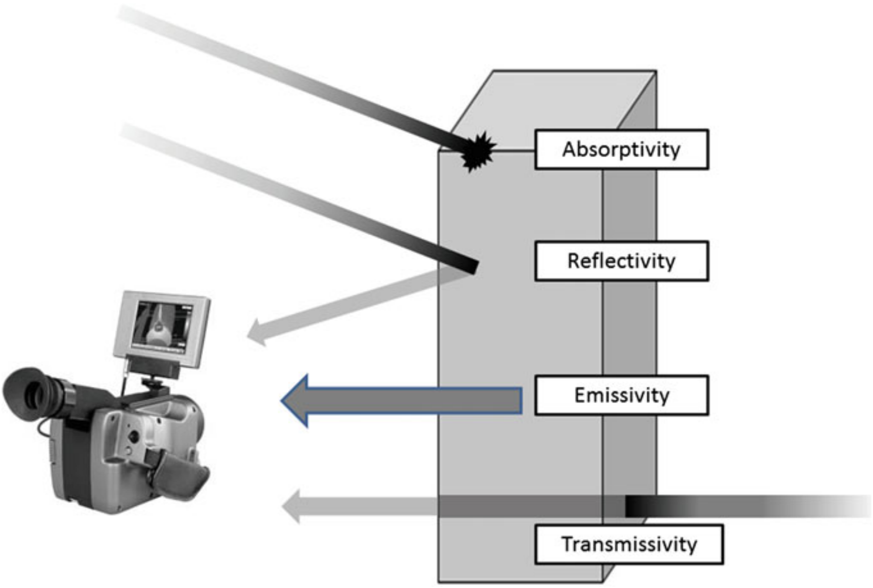

Fig. 2.12 Radiative characteristics of one body

The proportion of these components in a body are expressed by the following equations:

$$\alpha + \rho + \tau = 1 \tag{2.7}$$

Equation 2.7. Destinations of the incident radiation in a body: absorbed (α), reflected (ρ) or transmitted radiation (τ)

$$\varepsilon + \rho + \tau = 1 \tag{2.8}$$

Equation 2.8. Sources of the outgoing radiation of a body: emitted (ε), reflected (ρ) or transmitted radiation (τ)

As we discussed in the previous section, a black body is an ideal with values of emissivity and absorptivity equal to 1, and without reflectivity and transmissivity, and is therefore considered to be the perfect infrared emitter surface.

In the calculation of the temperature of a body, it is essential, in order to have an accurate calculation, that the body presents a zero transmissivity and an emissivity as close as possible to 1. Bodies with high values of reflectivity will result in temperature calculations with many errors because most of the outgoing radiation comes from the environment.

Behaviour of different bodies can be different in the visible region compared with the infrared. And for this reason it is essential to know the radiative characteristics of the bodies. One important example is water. In the visible region, water is more transparent and reflective. However, in the infrared, the characteristics of water are different. In the infrared, the water is opaque, with a higher emissivity than 0.9 [21]. If we do not know the radiative characteristics at the beginning of a thermography swimming study, we will probably want to measure while the swimmer is submerged in water, but this is impossible because of the opacity of the water (Fig. 2.13a). Another example is glass. Glass is transparent in visible light, but is opaque in infrared. Therefore we cannot see anything that is behind glass (Fig. 2.13b). An example of this is that the infrared cameras used at airports as fever screening method require glasses to be removed, in order to measure the temperature of the inner canthi of the eyes.

In this sense, knowing the emissivity of a body is of vital importance. Emissivity is a number ranging from 0 to 1, and it can be interpreted as the ratio of the actual

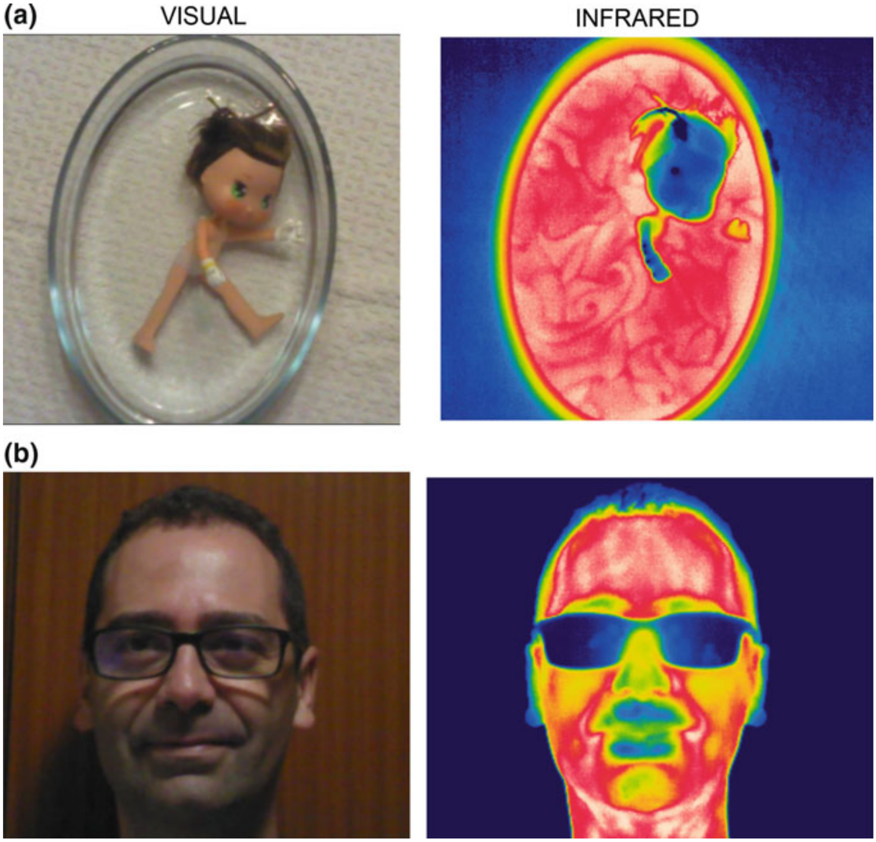

Fig. 2.13 Examples of the different behaviour of some objects in the infrared and visible spectrum. Infrared opacity of water (**a**) and glasses (**b**)

Table 2.1 Emissivity values of different materials

Material	Emissivity value
Skin	0.98 [23]
Enamel of human teeth	0.65 [24]
Cotton fabric	0.95 [25]
Water	~0.9 [21]
Aluminum (polished)	0.02 [26]
Black paper	0.9 [26]
Building materials: plaster	0.57–0.84 [27]
Building materials: porous stone	0.61–0.9 [27]
Building materials: marble	0.68–0.94 [27]

amount of infrared energy emitted compared with the theoretically perfect amount that could be emitted (black body) [22]. This means that one object with an emissivity value of 0.7 emits only the 70% of the maximum theoretical amount of infrared energy, and the other 30% of outgoing radiation comes from another sources. If we recall the modified Stefan-Boltzmann's equation, the emissivity was incorporated in the formula. The aim of this modification is to considerer only the percentage of radiation from the body, and to remove from the calculation the percentage of the reflected temperature. Table 2.1 presents the emissivity values of different materials.

In sports science, the most important "material" is usually the skin. **Skin emissivity** was determined with values between 0.97 and 0.99 with an standard deviation of 0.01 by different studies [23, 28, 29]. In scientific studies, an emissivity of 0.98 is commonly established. This means that the skin is a good emitter of infrared radiation and it is possible to accurately calculate its temperature.

However, for the thermography assessment of sports equipment and garments, it is necessary to know the emissivity of its materials in order to measure its temperatures correctly. In this sense, two strategies could be considered. First, it is of interest to review the scientific literature to determine whether previous studies have measured the emissivity of materials. The second strategy is to calculate the emissivity of a material or to check whether this emissivity measurement obtained is similar to that observed in the literature. The second strategy is always recommended because although is possible to find the emissivity value of one material, this value can be different in a given equipment/garment due to a different composition or different condition of the surface (e.g., polished, oxidized or scaled). Although there are more accurate methods, a method that is easy to perform and therefore can be carried out in any laboratory will be explained. This method consists of the following steps:

1. Attach a material with a known emissivity to the object of interest. Tapes with a known emissivity (with emissivity values between 0.95 and 0.99) are commonly used.

2. Heat the object of interest with the aim of having a higher contrast between the object and the environment. Ideally, this heat should be homogenous. For this reason, hot plates from laboratories are recommended.
3. Use the infrared camera to determine the temperature of the material with known emissivity.
4. Set the emissivity of the object of interest until obtaining the same temperature as the material with known emissivity. This is the estimation of the emissivity of the object of interest.
5. Repeat the experiment different times, at different temperatures and with different samples of your object of interest, in order to obtain a robust average of the emissivity.

After all these physical concepts, it is possible to better understand how thermal imaging cameras can measure temperatures from the detection of infrared radiation. In addition, the importance to know the radiative characteristics of an object with the aim to appreciate if it is possible to measure its temperature and the error during the measurement. The following section will discuss the processes of heat transfer and thermoregulation. These concepts are essential for the prediction and/or the interpretation of the thermographic results of an experiment.

2.6 Thermoregulation

Human thermoregulation can be defined as the integrative physiological responses of the body with the aim of maintaining core temperature within a few tenths of a degree of 37 °C, despite a wide range of activities and environments [9, 30]. These responses are coordinated mainly by the hypothalamus [30–32]. The hypothalamus integrates inputs from the temperature of the hypothalamus itself, the core and the thermoreceptors in the skin [30, 32, 33]. Furthermore, non-thermal factors also are responsible for the thermoregulatory response (e.g., sweating) [32] (Fig. 2.14).

To the three heat transfer processes detailed in the Sect. 2.2 (convection, conduction and radiation), it is necessary to add human body thermoregulation in terms of the **sweat evaporation** and **respiration**. Sweat evaporation is considered to be the main mechanism of heat dissipation during exercise. Evaporation results in a temperature decrease of the skin surface [1]. It is important to understand that it is the evaporation of sweat that is responsible for the temperature decrease and not the sweat production itself. Sweat rate is related to the ambient temperature, exercise intensity and absolute heat production [12]. In addition, the amount of evaporation is inversely proportional to the relative humidity of the air [9]. In an environment with 100% relative humidity, humidity could be condensed in the body resulting in a heat gain, at the same time as heat is lost by evaporation [9]. During respiration (specifically in the expiration), heat is lost to the environment via convection and

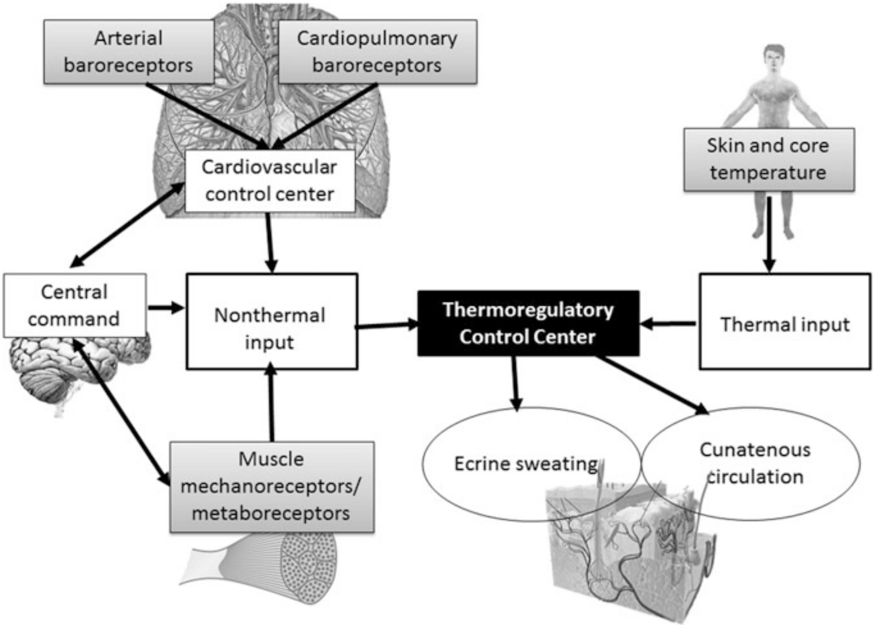

Fig. 2.14 Schematic representation of the human thermoregulatory system. Figure modified from Kenny and Journeay [32]

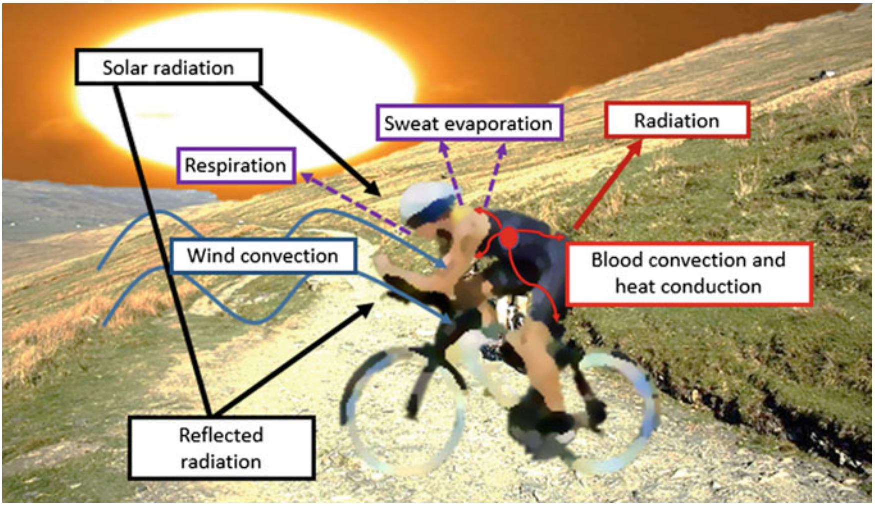

Fig. 2.15 Heat exchange between the body and the environment during exercise

evaporation [12]. Heat loss by respiration is higher in cold and dry environments; however, there is a low contribution of respiration in whole-body heat loss [12].

All these discussed processes are shown graphically in Fig. 2.15.

Following the first law of thermodynamics, the **heat balance equation** is commonly used in thermoregulation studies, where heat production is on one side of the equation and heat loss is on the other side. More specifically, this equation is defined as follows:

$$\text{M-W} = (\text{K} + \text{C} + \text{R} + \text{ESK}) + \text{S} \tag{2.9}$$

Equation 2.9. Heat balance equation where M is the rate of metabolic heat production, W is the rate of mechanical work, K is the rate of conductive heat loss, C is the rate of convective heat loss from the skin, R is the rate of radiative heat loss from the skin, ESK is the rate of evaporative heat loss from the skin, and S is the rate of body heat storage

All the concepts from Fig. 2.15 that have been discussed are expressed in the heat balance equation. However, there is one concept that we have not yet discussed and that is heat production. Heat production is the difference between metabolic heat production and the rate of mechanical work (M-W). Metabolic heat production was defined by Cramer and Jay [12] as "the rate of free energy released from the catabolism of carbohydrate, fat, and amino acids to resupply adenosine triphosphate (ATP) for cellular activities such as biosynthesis, transport, and muscular contractions". Some of this energy is converted in external work (W) and the rest is converted into heat [12]. For this reason, heat production is the difference between all the energy produced (M) and the energy used for external work (W). The body is very inefficient in transforming the energy in mechanical work, and between 30–70% of the energy produced, depending on activities, results in thermal energy [11]. Heat production is usually calculated by the combination of ergometers, which measure the work and indirect calorimetric measurements (gas exchange) that measure metabolic heat production [12]. Exercise results in an increment in heat production that the body needs to dissipate. We can exemplify how heat production increases with the intensity of the activity using different values of heat production. The heat production of sleeping, walking, cycling at 250 W and running at 16 km/h are 1.0, 4.0, 13.3 and 20.0 W/kg, respectively.

It is important to know the processes of human thermoregulation during exercise with the aim of obtaining the maximum possible performance and protecting athletes from injury, especially in extreme environments [31]. Thermoregulatory responses are different depending on the thermal environment (neutral or moderate, cold and warm/hot) [30]. Exemplification of the two most extreme scenarios help us to better understand human thermoregulation.

In warm/hot environments, the main objective of human thermoregulation is heat dissipation. This heat dissipation is mainly produced by two mechanisms, cutaneous vasodilation and sweat evaporation [9, 30]. Cutaneous vasodilation consists of the increase of skin blood flow in order to transfer the heat from the core to the body by the blood [30]. It is important to considerer that during exercise in hot environments, there is a “competition” between the active muscles and the skin for the available cardiac output, resulting in an increase in cardiovascular stress [34]. In sweat evaporation, the evaporation reduces the skin temperature. It increases the heat transfer from the core to the skin [30]. In addition, heat acclimation (heat exposure during a time) produces adaptations in these mechanisms [35]. Core temperature is reduced due to an increase in skin blood flow and sweating [35]. Furthermore, the volume of plasma is increased in order to minimize dehydration during exercise [35]. Figure 2.16 shows the adaptations to heat exposure in relation to the exposition time.

In cold environments, the main objective of human thermoregulation is heat conservation. Two of the main mechanisms of heat conservation are cutaneous vasoconstriction and thermogenesis [9, 30]. Cutaneous vasoconstriction consists of the opposite process to thermoregulation: skin blood flow is reduced in order to avoid heat dissipation via convection. Thermogenesis is produced mainly by shivering. Shivering consists of involuntary contractions of skeletal muscle with the aim of producing more heat [30]. Cooling acclimatization is a complex process with different patterns depending on the type and severity of chronic cold exposure [33]. The first adaptation is habituation, consisting of a less pronounced physiological responses (e.g., vasoconstriction and shivering) [33]. The second adaptation is an increase in heat production due to an exaggerated shivering or development of nonshivering thermogenesis [33]. Finally, there are insulation-related adjustments resulting in an enhanced vasoconstrictor response to cold exposure [33]. Figure 2.17 shows the schematic diagram of these adaptations.

During exercise, clothing affects heat exchange. Clothing increases insulation and reduces the convective and evaporative heat loss [37]. Furthermore, if the clothing is excessive, it can increase sweat production in response to decreasing core temperature,

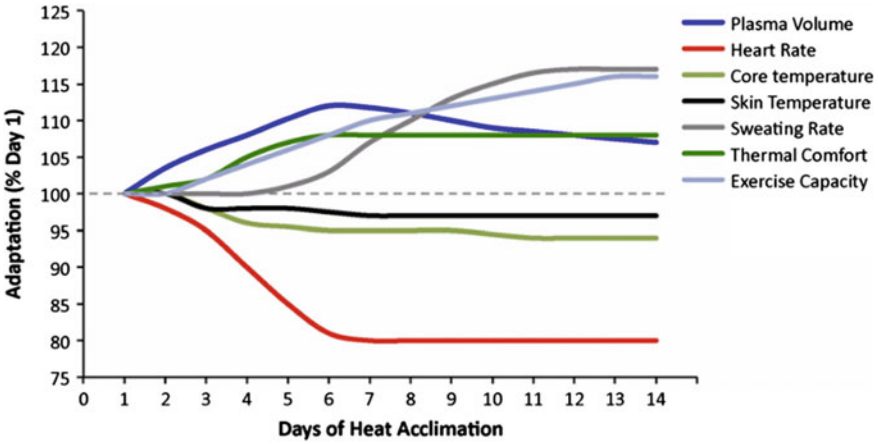

Fig. 2.16 Heat acclimatization adaptations. Figure obtained from Périard et al. [36]

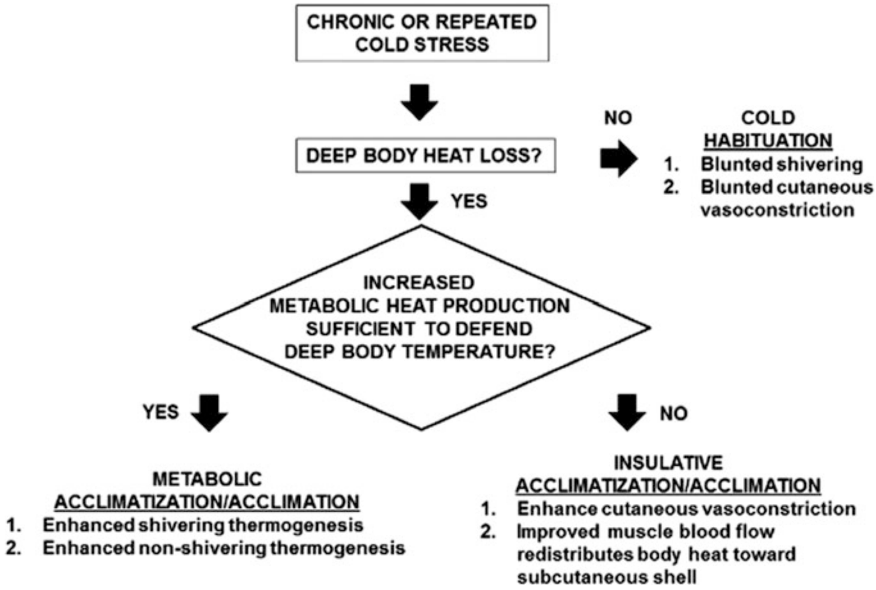

Fig. 2.17 Different patterns of human cold acclimatization. Figure obtained from Castellani and Young [33]

but this is not accompanied by efficient sweat evaporation [37]. Sweat or vapor may travel through clothing and it may be sorbed and desorbed by the textile fibers, or may condensate in the outer layer if these are colder than the skin [38]. This could result in an increase of the skin wetness and then a lower thermal comfort. For these reasons, usually the demands for sport clothing are based on allowing sweat evaporation [37]. However, these demands will be different for each kind of environment. Thermoregulatory aspects related to sports clothing will be discussed in the Chap. 7 of this book.

2.7 Conclusions

Infrared thermography researchers in sport science need to have knowledge about the physical principles of infrared thermography, heat transference and thermoregulation. This knowledge is necessary in order to understand the operation of infrared camera, to avoid and to know methodological issues, to establish logical hypotheses, and to correctly interpret the thermal results. Different conclusions can be extracted from this chapter:

- All the bodies that present a temperature above absolute zero emit infrared radiation and infrared cameras are capable of capturing this radiation. However, depending on the body, its emission is in a specific range of the infrared spectrum.

For some specific applications, such as the visualization of gases, special cameras are needed.

- Radiated energy from a black body is proportional to the fourth power of its absolute temperature. This relationship explains the high sensitivity of thermal cameras.
- It is necessary to know the radiative characteristics of a body in order to know if it is possible to calculate its temperature and to design a study without errors. In this sense, estimation of the temperature will be more accurate in bodies with high emissivity values. Skin is a good emitter of infrared radiation (emissivity of 0.98), which is important in sport science studies, because it is commonly the "material of interest". However, for other materials, it is necessary to know its emissivity values in order to correctly calculate the temperature.
- It is necessary to understand heat transference mechanisms in thermography studies. More specifically, in human studies, it is necessary to understand the mechanisms involved in the thermoregulation.

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Chapter 3
Methodological Aspects of Infrared Thermography in Human Assessment

Jose Ignacio Priego Quesada, Marcos Roberto Kunzler and Felipe P. Carpes

Abstract Infrared thermography presents some important advantages in the determination of skin temperature, as it is a safe, non-invasive and non-contact technique with wide applications in the field of sports sciences. Like many others techniques, valid measurement in thermography requires following strict methodological steps from data acquisition to analyses and interpretation. In this chapter, we discuss the methodological aspects that must be taken into account when acquiring thermic images, along with some practical examples and recommendations based on the current literature.

3.1 Thermography: Advantages and Limitations

In recent years, infrared thermography has become a popular technique to determine the temperature of human skin during exercise [1–4]. The reasons accounting for its popularization were the technological advances permitting assessment in a variety of sporting conditions and the more accessible price of the cameras. Previously used mostly with engineering applications, thermography became known by sports scientists who detected its potential for field assessment of physical activity and sport.

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Many recent studies are available presenting data from experiments that can illustrate the different applications of thermography in the assessment of exercise performance [5–7]. However, thermography in sports is still a recent topic and there are many fundamental discussions concerning different methodological aspects (e.g., determination of the regions of interest, strategy for analysis of the data, etc.), protocols of data acquisition, and the interpretation of results concerning its physiological or even mechanical meaning in the context of sports performance. Although the practice of infrared thermography has become more and more popular, these points of concern need further research. The good news is that the implication of the skin temperature information on athletic training is endorsed by basic research. For example, high skin temperatures are known to reduce the temperature gradient between the skin and the core, limiting heat transfer and producing a negative effect on aerobic performance [8, 9].

It is true that infrared thermography presents some methodological advantages, but also has some limitations. All these aspects must to be considered when designing, developing and analyzing data from experiments involving infrared thermography. De Andrade Fernandes et al. [3] described some of the advantages and limitations of using thermography in the assessments of skin temperature in humans. In Table 3.1 we summarize the description of advantages and limitations presented by De Andrade Fernandes et al. [3] and we also include some additional comments concerning the relevance of each advantage and limitation mentioned by the authors.

One important advantage of infrared thermography over other methods to determine skin temperature is that infrared thermography is considered to be a **distance technique**, which means that the measurement can be performed without interaction with the environment or subject. This advantage is essential in some applications, such as the assessment of electric or nuclear facilities in which the evaluator can analyze the components without being in danger. In the context of human assessment, this characteristic is also beneficial in order to determine skin temperature without interference in the processes of heat exchanges via convection, conduction, radiation and evaporation [3, 10, 11]. This is an inconvenient aspect of the sensors based on thermal contact, such as thermistors and thermocouples (see the circle in the Fig. 3.1). It is known that the interaction between these sensors, the skin and the environment can reduce the reliability of the measurement [12]. Additionally, the method used to attach these sensors to the skin (e.g., the clinical tape used) has been shown to affect the local heat transfer [13, 14], and hence the local thermal regulation and skin temperature might be altered [3, 10, 11, 15].

The **non-invasive** and **non-harmful** characteristics of infrared thermography make it a very attractive technique in medical areas, since it allows human physiological study without the risk invasive radiation presents in other imaging techniques (e.g., X-rays) [7, 16]. One attractive application of thermography is to detect injury. However, the association between thermographic data and injury remains debatable [16], although it has been used as an complementary tool in the physical examination [17, 18]. Some physiological disorders are associated with an alteration of skin temperature in the patient [7, 16]. In the context of sports injury, there

Table 3.1 Advantages and limitations of infrared thermography in human assessment (modified from De Andrade Fernandes et al. [3]) and its implication for using or not using thermography in assessment protocol

Advantages	Why is it an advantage?	Limitations	Why is it a limitation?
1. Non-invasive method 2. Distance method 3. It does not interfere with the human thermoregulation 4. Freedom of movement during exercise 5. Possibility to define the region of interest with small or large regions 6. High sensitivity, accuracy and reproducibility 7. Possibility to record video with some camera models	1. There is no physical interaction with the subject 2. It is possible to take the measurements without interference with the actual performance of the subject 3. There is no interaction that can affect skin temperature during measurement (e.g., isolation and reduction of sweat evaporation for the tape attachment of contact sensors) 4. Being able to measure without additional contact with the subjects (or with wires), movement patterns have more chance of occurring naturally 5. As many different regions as desired can be measured and monitored. Is not measuring a single point, as with thermocouples 6. Can provide very good and confident results, if the experiment is performed accordingly to the methodological requirements 7. Measurement can be performed at different times or even during a performance that can result in significant variation of skin temperature	1. High cost of the high definition cameras 2. Low resolution of the low-price cameras 3. The need for specific training of the user in the control of the different factors that could affect the measurements 4. The need to stop exercise and take the images during a static position when the camera does not have the video option or the exercise space could affect the measurement 5. Long time required to analyze the thermal images because the analysis software provided by the manufacturers is not specific to human assessment	1. The greater the definition needed, the higher the cost. It limits access to the technique 2. Cheaper options of camera can be good for learning the technique, but will not provide results good enough to draw scientific conclusions 3. Inter-user variability is high and affects the measurement. Therefore, specific training is necessary, which may increase costs in implementing the technique 4. Measuring skin temperature during exercise can be more "realistic" and can present more reliable results than static measurements 5. Data analysis still limited when considering big databases

Fig. 3.1 Thermal contact sensor attached to the skin during cycling (inside the *circle*)

are some studies discussing the potential associations between local temperature and specific injuries, but conclusions are still vague and further investigation is needed [7, 19].

One possible reason for the lack of relationship with some physiological manifestations of diseases or injury is that infrared thermography allows determination of **surface temperatures**. While very useful for discussing heat dissipation, inferences on central or tissues temperature are not possible. Some studies used infrared cameras to obtain direct data from deep tissues such as muscles, and this approach is limited due to all the processes of heat exchanges via convection, conduction, radiation and evaporation, that make the temperature from the internal tissues and the superficial skin temperature differ [20]. Furthermore, neuromuscular electrical activity, even measured by surface electromyography in the muscle, does not show a significant relationship with skin temperature in most of the lower limb muscles involved in the pedalling gesture [21]. However, there are many situations in which information regarding skin temperature is useful. The information about heat dissipation in the different body sites and the responses to exercise are important in the context of sportswear design [22] or in the assessment of the capacity of heat dissipation due to the physical fitness level [1, 4].

To draw consistent conclusions, **accurate data** are essential. To achieve this, a **rigorous methodology** must be followed [17, 23, 24]. Infrared thermography camera captures the infrared radiation, and the different levels of radiation define a thermal image. However, the proper determination of the temperature from this infrared radiation depends on technical and methodological factors that can influence the capture and the determination of temperatures (e.g., angle and distance of the camera, emissivity, etc.). Therefore, it is very important to strictly follow a protocol for the image acquisition. The main aspects that must be taken into account during image acquisition will be discussed in the next sections.

3.2 Methodology for Infrared Thermography Assessment in Humans

Different organizations proposed standard recommendations for the use of thermal imaging in studies with humans. Some examples are the technical guidelines published in 1986 by the American Academy of Thermology [25], the guidelines for neuromusculoskeletal thermography published by the same association in 2006 [26], and the Glamoral Protocol published in 2008 by the European Association of Thermology [23]. However, different methodological aspects remain unclear and, for this reason, researchers are still working to clarify different issues. To this end, recent scientific articles analyzed specific aspects of the methodology and thermography outcomes in human assessment [11, 27–30]. Taking together guidelines and publications, the main methodological aspects for assessment of humans with thermography should attempt to:

1. Reduce the error of measurement of the infrared thermography camera (minimum error is commonly established by the manufacturers at ±2%).
2. Reduce the variability in the measure of the skin temperature between participants.
3. Increase the reproducibility of the measurements.

To achieve these three methodological concerns, both technical and methodological requirements must be considered and, more importantly, must be carefully administrated to improve the measurements and therefore lead to valid conclusions. The next sections will introduce each of these requirements.

3.2.1 Determination of the Region of Interest (ROI)

Determination of the ROI is one of the most important steps in the design of a thermography study. The determination of the ROI will depend on the purpose of the study. Therefore, the ROI must be determined in the early phase of study design because this will affect other aspects such as the body position during the thermal room adaptation or the position of the camera. The variables of interest, such as descriptive statistics, will be extracted from each ROI obtained from the thermal image. Determination of the ROI is important because it can also help in improving data acquisition quality, especially when camera resolution is limited. ISO normative determines the size of the ROI. To reduce error, a minimum of 25 pixels is recommended [31, 32]. The camera should be placed as close as possible to the ROI in order to increase the number of pixels of measurement [33]. Additionally, the size of the ROI will directly influence the temperature measurement, as a smaller ROI will present a higher temperature than a larger ROI due to the greater influence of hot spots in these smaller areas [11].

The Glamorgan Protocol was published in 2008 with the purpose of standardizing the ROIs determination in thermographic studies [23]. This document presents the definition of 90 different ROIs. Although the Glamorgan protocol provides important guidance in the determination of the ROI, there are a number of studies with very specific demands. Because of this, researchers have developed their own criteria to define ROIs, with different geometries and methodologies [24, 30]. Differences in skin temperature between ROIs are due to the tissue composition, muscular activity and capacity of sweating [21, 29, 30, 34], and these factors are important to take into account during the definition of the ROI.

The reproducibility in the determination of the ROIs for different images is another important factor in ensuring the accuracy of the results, especially when different subjects are compared. Different strategies were observed in the literature in order to increase the reproducibility of thermographical data. Some researchers use software with an automatic ROI selection feature [22, 35, 36]. However, these software are not accessible to all users, and for this reason one of the most used strategies is the determination of ROI according to anatomical proportions [21] or body segments [37–39].

Mathematical methods can also be used in the determination of ROIs. One example of this is the Tmax method, which was proposed by Ludwig et al. [27]. In this method, the operator selects an ROI and the software will automatically select the five warmest pixels within the ROI, with a minimum distance of at least of five pixels between each. The software selects an area of five × five pixels around each of the five pixels previously selected, determining the mean temperature across the 125 pixels included in the selection [27]. These authors suggested that the main advantage of this method is the use of the same number of pixels for the calculation, removing the effect of the different anatomical sizes between participants [27].

It is also possible to determine the ROIs using markers in anatomical references or outer delimiting areas of the body surface (Fig. 3.2) [7, 29]. This strategy can be useful in ensuring the reproducibility in the delimitation of the ROI and it facilitates further data analysis. After this recapitulation of information, we can provide some overall recommendations for the determination of ROIs:

- To record the maximum number of pixels of the ROI in the thermal image, put the camera as close as possible to the region (always considering that the image must be focused). A higher number of pixels will provide more robust descriptive statistical data relating to the ROI.
- Whenever the objective of the study permits, use large ROIs instead of small ROIs. The large ROIs will reduce the possible effects of punctual points of the ROI such as hot spots.

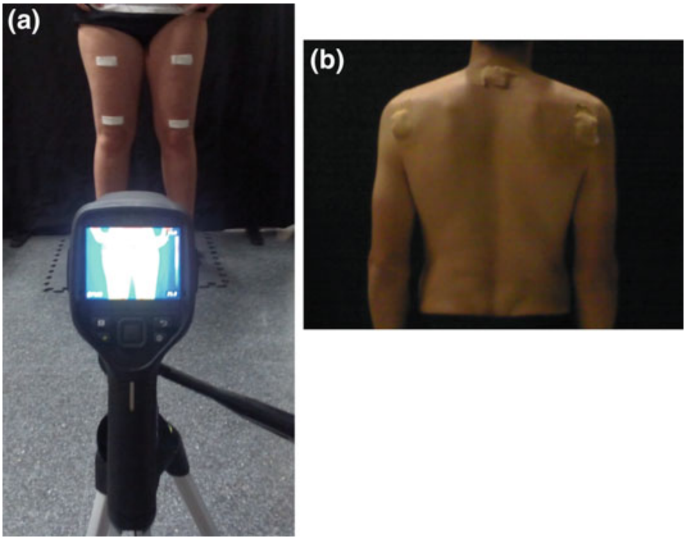

Fig. 3.2 Examples of the use of markers to delimit the ROIs in the quadriceps (**a**) and back (**b**)

- To reduce the subjective aspect for the delimitation of the ROIs as far as possible, increase the reliability. Software with automatic ROI selection, the use of markers in the skin, or the delimitation using anatomical references are strategies that can help in this objective.
- To determine the ROIs, take aspects like tissue composition, muscular activity and capacity of sweating into account. In this sense, we recommend avoiding measurements in the same ROI, regions in which the muscles are close to the skin (e.g., thigh or leg) and regions with a higher proportion of bone and connective tissue close to the skin (e.g., knee or Achilles).

3.2.2 Methodological Aspects of the Camera

The **choice of camera** is an important step in the use of thermography. Cameras for thermographical assessment can be cooled or uncooled cameras (Fig. 3.3). Cooled cameras normally operate at cryogenic temperatures [40]. The older cameras were cooled by the addition of liquid nitrogen, argon gas or sterling cooler, resulting in a limitation of the angle of operation of the camera [40–42]. In this case, a high camera angle could put the liquid nitrogen or other cooling system in contact with the electronics and cause damage. Other cooling systems (e.g., thermoelectric systems) were introduced to overcome the angle problem of the camera [40, 41]. The cooling system is usually associated with power and time taken to cool the camera, and it is bulky and expensive [33, 40]. However, the cooled detectors

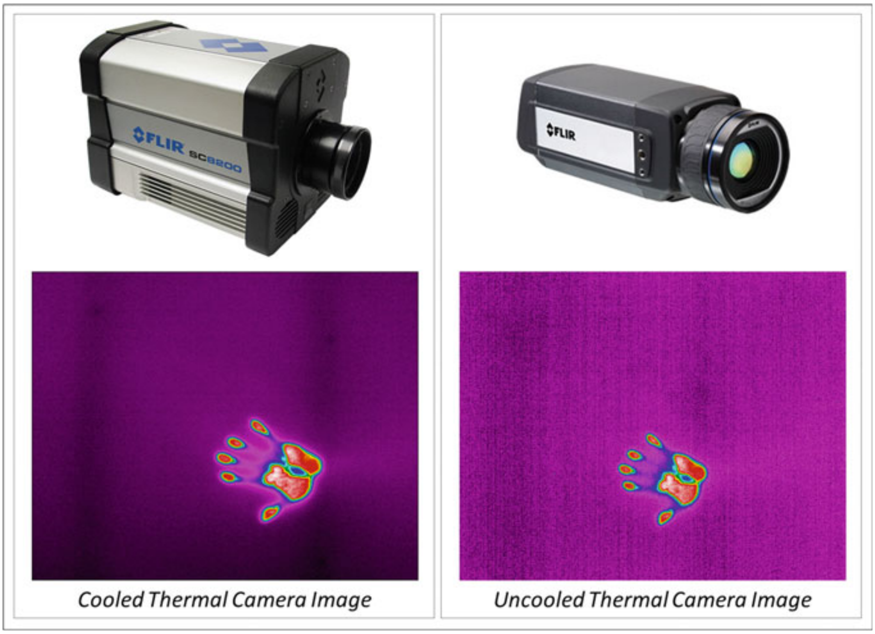

Fig. 3.3 Examples of cooled and uncooled cameras and respective image record (figure modified using images from the FLIR website)

provide a superior image quality and a greater sensitivity to small differences in the scene temperatures than the uncooled detectors [33, 40]. The more recent generation of uncooled cameras can be used without cooling, but using a microbolometer [42]. These cameras will be stabilized at ambient temperatures using temperature control elements (based for example on changes on resistance and voltage) to reduce the image noise [40]. Although these cameras provided a lower quality of image and have lower sensitivity, they are less expensive in price and maintenance, smaller and easier to use [40, 41].

Also related to the choice of the camera, **infrared resolution** is an important technical aspect to be considered (Fig. 3.4). Although infrared resolution is not the most important factor in the accuracy of the calculation of the temperature [43], it is always preferable to have a camera with the best resolution that you can afford [24]. Each pixel in the thermal image represents one thermal data, and a higher number of pixels will result in a more robust measure when average temperature is calculated in the ROI. One example of this is that 25 is considered to be the minimum number of pixels to determine average temperature for a region of interest for the ISO normative [31, 32]. In this regard, an infrared resolution of 320 × 240 pixels is commonly considered to be the minimum resolution necessary for satisfactory data in the human assessments [7, 24].

For sports science applications in particular, the capacity to **record thermographic video** is an important feature in the thermographic camera. There are a few

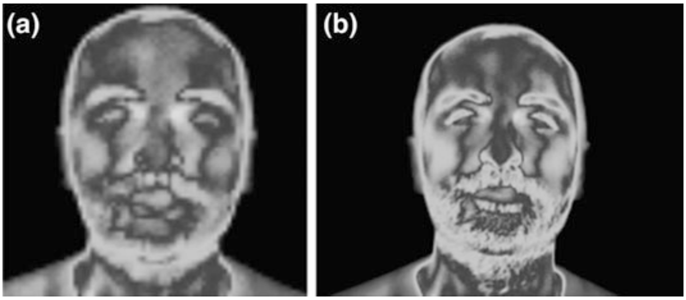

Fig. 3.4 Example of the same image recorded with an infrared camera with a resolution of 140 × 140 pixels (**a**) and with an infrared resolution of 320 × 240 pixels (**b**)

studies using this feature in sport assessment [2, 44, 45]. Despite the higher cost and specific configuration required for proper image acquisition during thermographical video records, the calculation of the temperature in an sports assessment could be disturbed by nearby electronic equipment (e.g., ergometer, computers, etc.) [41]. This is the reason why researchers usually try to analyze static images recorded before and after exercise [11, 46].

As observed in many other instruments, a proper calibration is also necessary for thermographical assessment. Infrared cameras are calibrated by the manufactures with a high number of black body sources at different temperatures when the signal of each pixel is determined [47]. A black body source is an instrument with a stable and accurate temperature surface, with a high emissivity, configured with a specific temperature emission (Fig. 3.5). These black body sources usually have an emissivity as high as 0.98 [47]. In addition to the manufacture calibration, in research studies, the camera usually is calibrated again before every experiment starts. To do this, the black body sources need time to stabilize temperature before the calibration. The calibration is more precise when the black body source is set at a higher temperature than the room temperature, and it is important to know the accuracy and the emissivity of the black body source in order to perform the best calibration possible. For example, black body source can be configured to some specific

Fig. 3.5 Examples of black body systems

temperature emission (e.g., 50 °C). When the black body is stabilized, thermography camera can record a thermal image where is the black body. After that, we can analyze the difference between the temperature of the black body source in the thermography and the set temperature of the black body source. If the difference is inside of the accuracy of black body source, the camera is measuring correctly, but if we have a higher difference, we can compensate this difference in the data analysis. However, if the difference is very high it is recommendable to send the camera to the manufacturer for calibration. In addition, the black body (and also a black plate thermistor) can be placed in the space of measurement in order to have this reference in the image, which also permits any drift in the temperature sensitivity during the laboratory daily routine to be checked and increases reliability [17, 41] (Fig. 3.6).

Another important aspect to consider is that the camera should be turned on some time before the measurements start. Infrared thermography cameras have a condenser to stabilize the electronics and compensate its temperature variations. However, it needs time to adjust to the environmental conditions and to work properly. The time necessary for this stabilization may differ between camera models. For example, the minimum time determined for the uncooled camera used by the authors of this chapter was 5 min [30]. However, since their camera measurements became stable after 5 min of turning on the camera, they determined a 10 min stabilization period to ensure this process [30]. There are cameras that may need a minimum of 10 min to stabilize [47]. The most common procedure to ensure camera stabilization time is to set some system with a stable temperature (black body source or hot plate system), turn on the camera and record thermal images continuously. When there is no variation in the temperature data with the time, it means that the camera is stable.

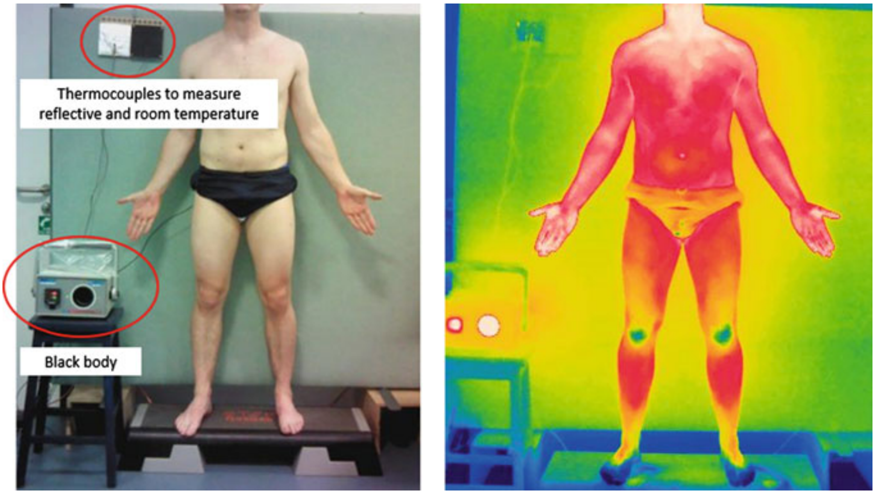

Fig. 3.6 Examples of different references (black body and thermocouples) placed in the space of measurement to increase the reliability

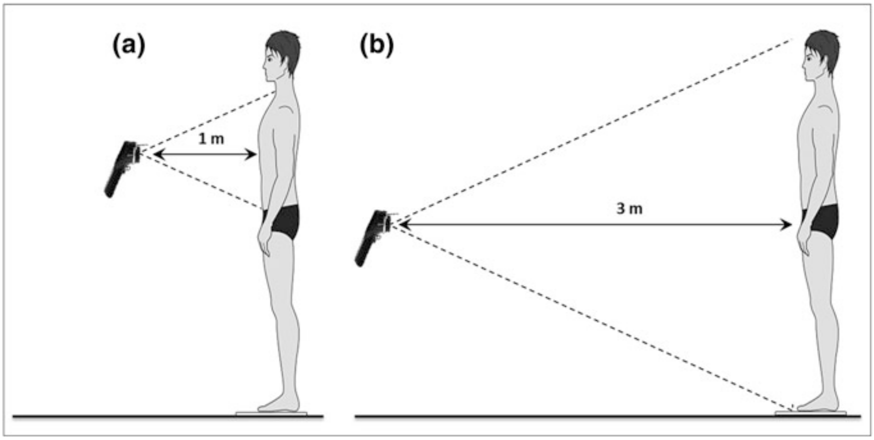

Fig. 3.7 Example of the position of the camera in relation with the ROI

The position of the camera (**distance** and **angle** in relation to the ROI) can affect the measurements and needs to be controlled [48–50]. The camera lens should be placed perpendicularly to the ROI. Angles higher than 60º between the camera and the ROI considerably modify the data [50]. It is important to take all the thermal images of one study at the same distance to minimize these errors. In this sense, Tkáčová et al. [50] observed differences of 0.2 °C between measurements performed between 0.2 and 2.5 m between the camera and the ROI. Although the distance is an important parameter to control, it also depends on the infrared resolution of the camera and the ROI (Fig. 3.7). Most of the studies with humans registered the measurements at distances between 1 and 3 m [1, 3, 11, 22, 30, 39, 46]. The camera should be placed as close as possible to the ROI and record the highest number of pixels in that region [33]. In order to have some reference values, a distance of 1–1.5 m it can be enough for a ROI that is a body segment (Fig. 3.7a), and a distance of 3–4 m it can be the necessary when the ROI is all the whole surface of the subject body (Fig. 3.7b). Similarly, when taking thermographic images, the **focus** of the camera must be adjusted. Errors in the focus adjustment consistently produce errors in the temperature calculation of the ROI (see details in the Fig. 3.8).

3.2.3 Methodological Aspects Related to the Space Where the Measurement Will Be Conducted

Considering the space measurement, the main methodological aspects to take into account are the room space, the room temperature, the relative humidity, and all sources of infrared radiation that might affect the thermographic measures by

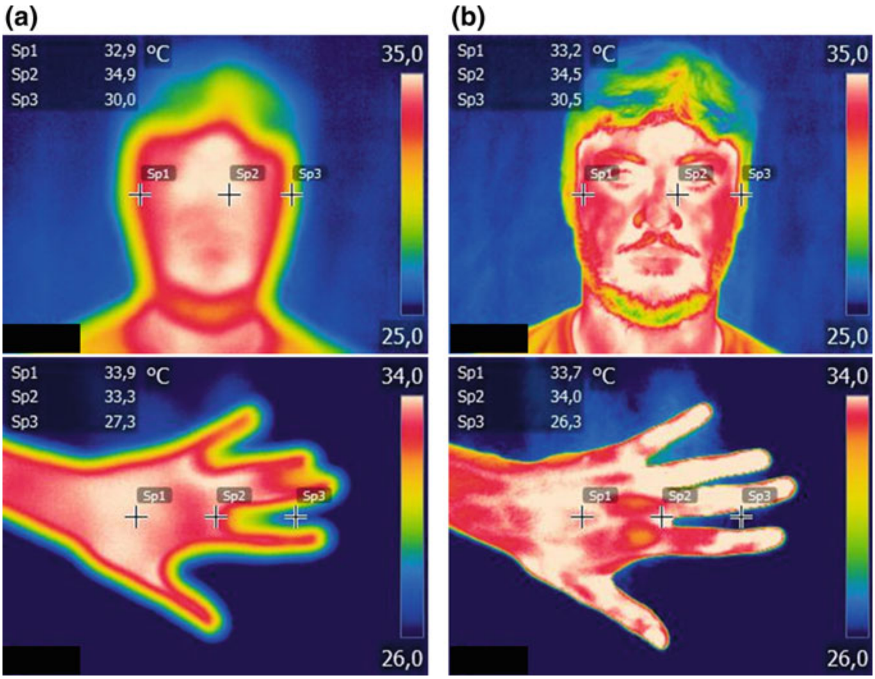

Fig. 3.8 Example of error calculation in images with an incorrect (**a**) and correct (**b**) adjustment of the focus

standing around the subject. The parameters of the room temperature and its relative humidity must be informed in the camera setup. The **minimum space** dedicated for the measurement is 6–9 m^2, but spaces of 12 m^2 are preferable [41, 47]. The **room temperature** is one of the most important factors affecting skin temperature, because both are directly related [51–53]. Different authors have suggested that room temperature should be between 18 and 25 °C during thermography assessment with humans [42, 49]. This is because the room temperatures outside of this range could affect the thermoregulation mechanisms, resulting in sweating when the room temperature is higher than 25 °C, or shivering when the room temperature is lower than 18 °C [42]. Furthermore, temperature variation in the room should be no higher than 1–2 °C. When data from measurements made in the trunks of 64 male cyclists were analyzed, it was observed that an increase of 1 °C in the room temperature resulted in 0.35 °C higher skin temperature ($r = 0.5$ and $p < 0.01$). This influence was minimized when temperature variations (difference before and after) were determined (Fig. 3.9). Ring and Ammer suggested that an environmental temperature of 20° is better for visualizing inflammatory injuries [41]. Therefore, the ideal environmental temperature for thermographical measures may depend on the purpose of the experiment.

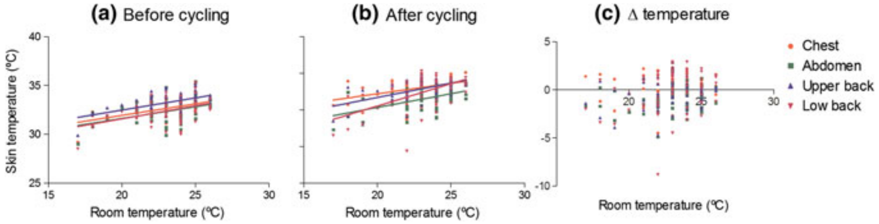

Fig. 3.9 Influence of the room temperature on the skin temperature measured before (**a**) and after cycling (**b**). The influence was removed when skin temperature variations (difference between temperature after and before cycling) were assessed (**c**)

The **relative humidity** in the room where the measurements are taken affects the sweat evaporation rate during physical activity and sport performance [54]. The influence of relative humidity can be higher when the camera is positioned far from the ROI [47]. It is recommended to control relative humidity to values between 40 and 70% [1–4, 11, 22, 38, 46, 55, 56]. It is also important to avoid the presence of particles in the air, such as dust or vapor, because these can absorb the radiation emitted by the participant and therefore cause measurement errors because all the infrared radiation of the participant does not arrive at the camera.

Reflected temperature is defined as the temperature of other objects that are reflected by the target into the infrared thermography camera [57]. This temperature should be measured and informed during camera setup configuration. The software of the camera will disregard this parameter from the calculation of temperature of the ROI. It is recommended to measure the temperature reflected in each test. The reflected temperature can change when the environmental conditions change (e.g., variation in the room temperature), the conditions of the evaluator (e.g., changes in clothing) or any feature of the space changes. One of the most used methods to measure the reflected temperature is the "reflector method" described in the international normative ISO 18434-1:2008 [57]. This method consists of:

1. Informing the following parameters to the camera: distance with a value of 0 and an emissivity with a value of 1.
2. Positioning cardboard with aluminum foil at the same level as the participant (Fig. 3.10a).
3. Measuring the average temperature of the aluminum foil (using a rectangle ROI) (Fig. 3.10b).
4. Introducing the thermal average obtained, such as the reflected temperature.

The presence of **infrared radiation sources** close to the measurement space should be avoided. Infrared radiation sources include the incidence of sunlight in the space of measurement, the presence of electronic devices and the number of people in the measurement space (evaluator and participant). Other sources of radiation are heating ducts, water pipes, heating lights and airflow. Likewise, reflections of infrared radiation around the participant should be avoided, so we recommend placing anti-reflective material behind the plane of interest [7, 47].

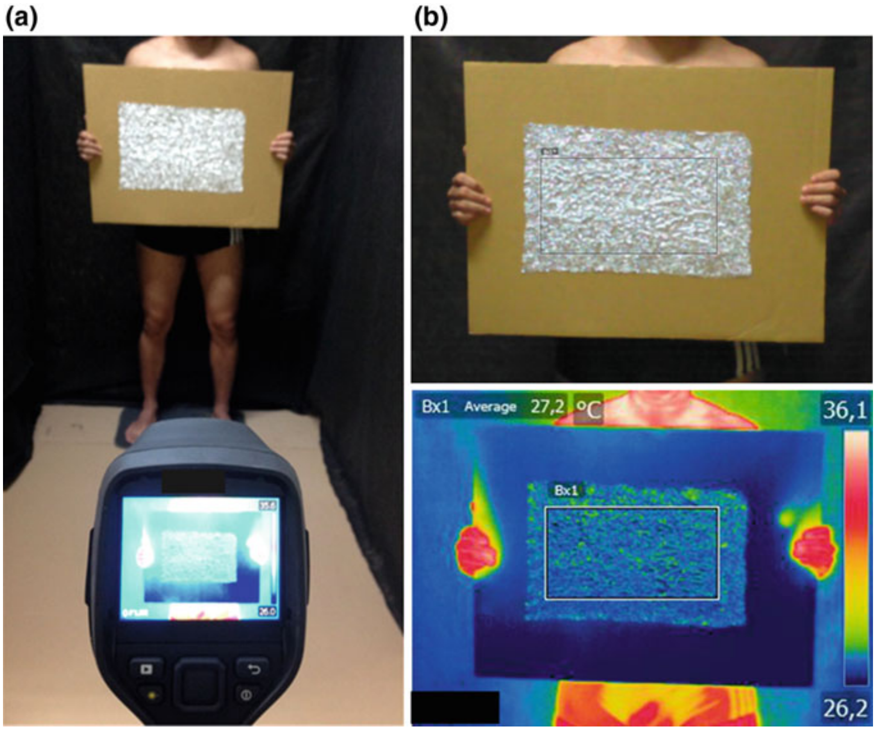

Fig. 3.10 Reflector method

3.2.4 *Methodological Aspects Related to the Person*

Considering the characteristics of the subject going to be evaluated, one of the factors to take into account is the **emissivity** of human skin. Different studies determined the skin emissivity and described values between 0.97 and 0.99 [58–60]. Thermographic studies with humans commonly consider an emissivity of 0.98 [1, 3, 7, 21, 22, 61]. These studies used this emissivity value for all the participants due to the lower variability observed—standard deviation of 0.01 [58, 60]. This standard deviation in the emissivity resulted in approximately ±0.05 °C or ±0.12% of change in the absolute temperature, and such error will be smaller than the thermal sensitivity of the camera or the variability of the skin temperature between participants and trials. These values of emissivity of the skin means that humans are a good emitter of infrared radiation, and therefore we can obtain accurate surface temperatures [59, 62]. The emissivity value must be introduced into the camera or thermographic software for the correct calculation of the temperature.

The thermal variability of the human skin temperature can be very high due to a great number of factors, such as the individual metabolism, blood flow, adipose tissue, etc. [24]. The present chapter has an applied orientation, and for this reason the factors will be classified considering the experimental process and when they will be taken into account: (1) in the design of the experiment; (2) in the criteria for selection of the participants; and (3) in order to elaborate the instruction that participants need to follow (Fig. 3.11). Some of the points related to the selection of the participants or instructions they will receive can be interpreted in a different classification depending of the researcher. For example, some researches will consider it important to classify the participant as a smoker or non-smoker in the inclusion criteria for the research, while for others such information will be pertinent when sending the instructions to the subject before the assessment. For this reason, it is important to understand that the authors of the present chapter do not think that their classification is the only one to be considered, but rather is the classification considered suitable for the purpose of this chapter. On the other hand, the most important aspects in which the thermography evaluator can act were addressed in this section. Other factors, such as genetics, were not addressed in this chapter.

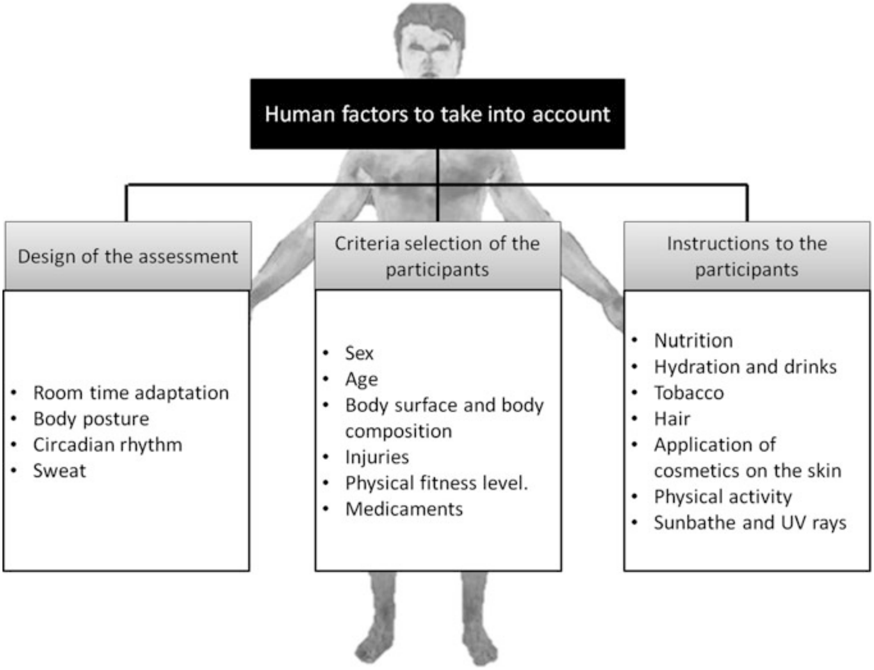

Fig. 3.11 Classification of the methodological aspects related to the person following the experimental process

3.2.4.1 Factors to Take into Account in the Design of the Assessment Protocol

Some factors are essential to take into account in order to obtain the maximum reproducibility in the accomplishment of thermographic measurements. The temperature of the skin usually presents high variability, which may limit the comparison of results between and within subjects. Therefore, some general recommendation can be followed to reduce these intervenient factors.

Room time adaptation One of the most important methodological aspects is the time required to achieve a stable measurement of skin temperature in a controlled environment [28, 41]. When the individual arrives at the measurement space (typically he/she comes from a different environmental temperature) and prepares for the thermographic measurements (e.g., undressing), it will produce a change in thermal conditions, and hence a variation in the skin temperature. Therefore, an adaptation period is necessary; otherwise the repeatability of the measurements will be very low because the external conditions of each day and each subject are different. During this adaptation time, the participant must avoid all the movements and contact that can affect the skin temperature of the ROIs; for instance, actions such as folding or crossing the extremities, placing bare feet on a cold surface, etc. [41]. In this sense, the use of a carpet or rug in the ground is recommended. Studies commonly use room time adaptation ranging from 10 to 20 min [4, 11, 21, 38, 56, 63, 64]. Longer periods are not recommended because when the time adaptation exceeds 30 min, the temperature oscillation are higher and may result in thermal asymmetries [28, 41]. Marins and colleagues concluded that a minimum time of 10 min is suitable for temperature stabilization, but they suggested that longer times can be required when participants come from extreme environments (cold or hot) [28].

Body posture Body posture during the image acquisition will be dependent on the ROI defined. Some examples and guidelines are present in the catalogue of ROIs described in the Glamorgan Protocol [23]. In this sense, the anatomical position is usually a very common position for thermal measurement using infrared thermography. However, there will be some cases not considered in that protocol and, for these cases, special attention should be given. The body posture needs to be the same during the whole room time adaptation [41]. In some exercises, it is possible to take the thermal images during the moments of force production or along the movement (e.g., in a static contraction or during a body segmental movement), [4, 64, 65]. We do not recommend comparison of thermal images taken in different body postures because the posture changes the body surface exposed to the environment and then the skin temperature may also be changed [17, 41, 66] (Fig. 3.12).

Circadian rhythm The circadian rhythm affects the core temperature [67, 68], skin blood flow [67] and skin temperature [69, 70]. Skin temperatures are lower in

Fig. 3.12 Effect of the body posture on the heat flow. Figure obtained from Houdas and Ring [66]

the morning and increase during the day [69, 70]. The hands are the body region with the highest increase in skin temperature during the day [69, 70]. These effects of skin temperature could be related to the same trend observed by Smolander et al. about the relationship between skin blood flow and the circadian rhythm [67]. In order to minimize this effect, some studies have performed all measurements in the same period of time [1, 3, 4, 27, 38]. Another possible strategy to reduce the intra-subject effect of the circadian rhythm, when the study has a cross-over experimental design, is to ensure that measurements of each participant are always performed at the same time of the day [55, 56].

Sweat Moistening of the skin surface due to perspiration may influence thermographic data [11]. Ammer [71] suggested that a film of water on the skin may act as a filter for infrared radiation and that could lead to an error in the estimation of the skin temperature. Removing the sweat or water from the skin has been tried as a solution [72, 73]. These studies [72, 73] tried to remove the sweat without friction of the skin. However, in other studies, temperature could increase as a consequence of rubbing the skin surface and also as a result of the reduction of the natural process of sweat evaporation [11]. On the other hand, the results of one study indicated that the accumulation of sweat during cycling is not enough to form a film of water, and that sweat produced under these conditions does not affect the thermographic data [11]. However, the influence of the sweat on the skin emissivity in infrared measurements as well as the possible strategies to deal with the effect of sweating on skin emissivity during thermographic examinations are unclear to date. Hence, future studies are necessary to explore this methodological aspect in more detail.

3.2.4.2 Factors to Take into Account in the Criteria Selection of the Participants

In order to reduce the variability of the skin temperature results, many factors should be considered. It starts with the definition of the criteria for the selection of the participants. Some of the most relevant factors are commented.

Sex Women present higher core temperature [68, 74], lower whole-body sweat rate [75] and higher percentage of body fat than men, which influences heat loss and results in lower skin temperature in most of the body regions [37, 76]. The lower heat production during exercise presented in women is another explanation for these lower skin temperatures [77]. These gender effects are more evident in the morning than in the evening, possibly because the blood flow is lower and then the thermal insulation effect of the body fat is higher [70]. It is also important to consider the influence of the menstrual cycle. Different studies have shown that core temperature [78, 79] and skin blood flow [80] were higher during the luteal phase than in the follicular phase resulting in a higher skin temperature in the women.

Age Older people present lower basal values of skin temperature [51, 64, 81] and after an intervention aimed at increase body temperature (e.g., exercise), a lower response of skin temperature was found among the elderly [51, 64]. The reasons for the skin temperature decreases with age may be related to a lower metabolic rate [82], lower core temperature [68], and the lower capacity of heat dissipation via vasodilation/vasoconstriction [51, 83] and sweat rate [82, 84].

Body surface and body composition Body surface has an important role on whole-body heat exchange [85, 86]. Individuals with a greater body surface have a greater capacity for heat dissipation [85]. This happens because they have a greater skin surface and then greater absolute rates of convection, radiation and sweat evaporation [86]. For this reason, in order to compare different groups or participants, it is recommended that some body surface variables be normalized (e.g., sweat rate; mg cm^{-2} min^{-1}). Body surface is usually measured using predictive equations considering the height and body mass, and one of the most used equations is the DuBois and DuBois' equation [87]. In relation to body composition, the level of body fat influences the capacity for heat loss resulting in lower skin temperatures [88]. Body fat tissue had an insulation capacity resulting in impairment in heat dissipation between the core and the skin [46, 88, 89].

Injuries An injury is often related to variations in the regional blood flow. Changes in blood flow affect skin temperature, which can increase in the case of an inflammation, or decrease in the case of tissues with poor perfusion, degeneration or reduced muscular activity [7, 42]. Individuals with overuse and traumatic injuries could present with an alteration of skin temperature and thermal symmetry [7, 42] (Fig. 3.13a). In addition, other disorders such as diabetic neuropathy, fever and vascular disease, among others, can influence skin temperature [16] (Fig. 3.13b). For this reason, studies selected participants without history of injuries in the previous months [3, 56, 90]. This is certainly a fertile topic for further investigation,

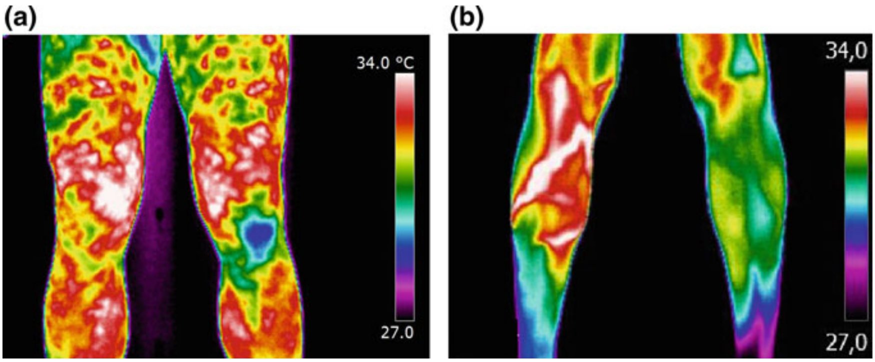

Fig. 3.13 Example of the presence of undiagnosed injury in the knee (**a**) and a varicose vein in the leg (**b**)

since the medical application of the thermography, as mentioned before, has many advantages over other imaging methods.

Physical fitness level Physical fitness influences skin temperature [1, 2, 4, 21, 46]. Larger heat loss is observed among participants with better physical fitness, which could be explained mainly through the higher capacity of evaporation of sweat during exercise [46, 91]. Moreover, trained people usually have greater capacity for heat transference between the core and the skin due to higher blood flow and lower body fat [21, 46, 89, 92]. The variability of fitness level will result in a high variability of the skin temperature if considering a heterogeneous group.

Medicaments Medicaments could alter skin blood flow and then skin temperature. It is known that different kinds of medicaments such as analgesics, anti-inflammatories, vasoactives, hormonal medications, prophylactics and anesthetics can affect the normal values of skin temperature [24]. Furthermore, infrared thermography was used in different studies as a method to determine the response of a medicament [93–96]. In human assessment, when the objective of a study is not to assess a medicament, it is common to recruit participants without a medicament prescription or to avoid the intake of medicaments before a study in order to remove this factor [1, 4, 38, 90].

Factors to Take into Account in Instructing Participants

It is suggested that participants be instructed by means of a previous session or by means of a written letter or email containing the information and procedures necessary to avoid possible measurement errors. When possible, a familiarization session can be very valuable in order to fully address all the factors that can influence measurement. Some of the most important factors are described below.

Nutrition It is commonly established that after food intake, blood supplies the stomach to the detriment of the skin, resulting in a lower skin temperature in the extremities [97, 98]. Heavy meals approximately 4 h before the measurement should be avoid for the human thermography assessments [1, 21, 30].

Hydration and drinks Prior to the thermographical assessment, it is important to ensure that the subject is adequately hydrated. Hipohydration can affect the sweat rate response and then the skin temperature, as detected by infrared thermography [99]. On the other hand, intake of different liquids has been associated with alteration of skin temperature. For example, alcohol intake increases skin temperature due to the increase of the skin blood flow [100–103]. Liquids with caffeine, and others stimulants such as teas, stimulate the physiological function, resulting in an increase in skin temperature [104–106]. For these reasons, participants of the studies are usually requested to avoid ingestion of alcoholic or caffeine at least 4 h [1, 27, 38] or, preferentially, 12 h before the measurements [21, 30, 56].

Tobacco It is well established that nicotine has a vasoconstrictive effect and therefore it may reduce skin temperature [107–109] (Fig. 3.14). In addition, it is known that smokers have a reduced circulatory system compared with non-smokers (e.g., they have impaired capillary recruitment and impaired vasodilation) [109]. Thus, it is usually recommended that thermographic studies do not include smokers [1, 38], or that smokers are instructed to avoid smoking for 12 h before the measurement [21, 30, 56].

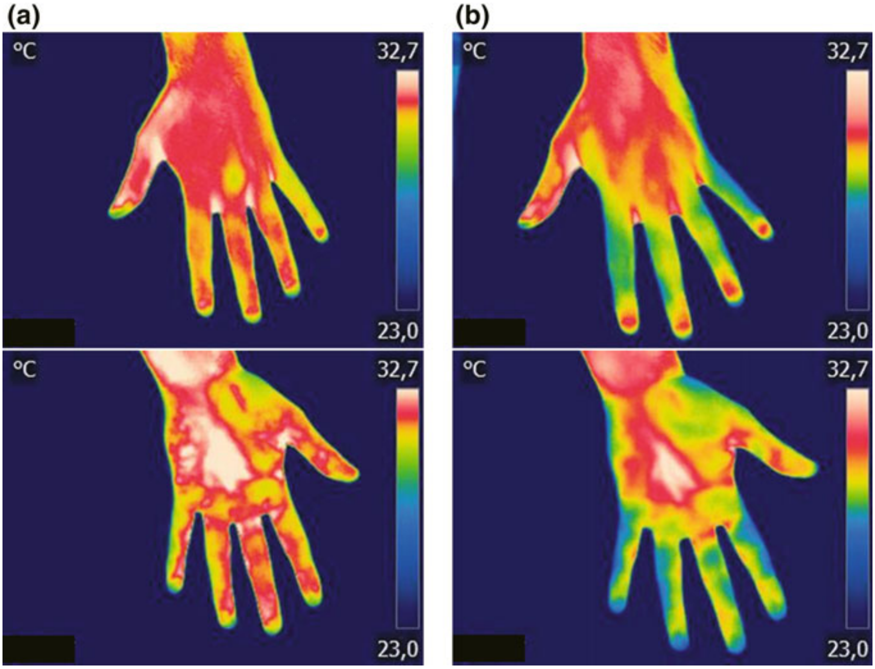

Fig. 3.14 Example of the effect of smoking on skin blood flow and then in the skin temperature. Thermal images were taken before (**a**) and after smoking (**b**)

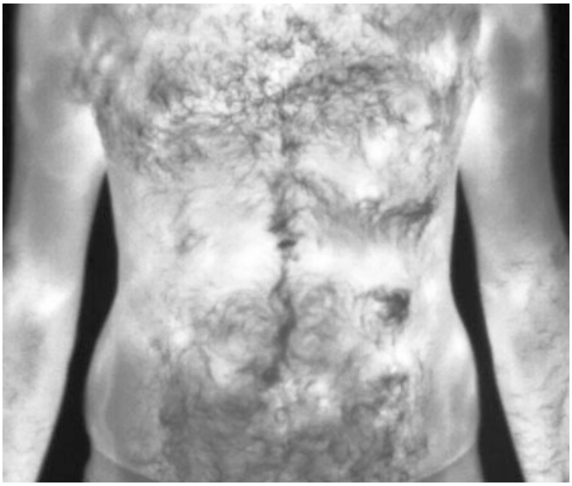

Fig. 3.15 Example of thermography of the chest of a subject with hair

Hair The presence of the hair on skin surface can alter the estimation of the skin temperature using infrared thermography [24]. Hair is an avascular tissue [110] with a low heat capacity and then with a lower temperature [111] (very similar to room temperature). For this reason, if there is a high hair density in the skin, this hair could be considered to be an artifact resulting in an underestimation of the skin temperature (Fig. 3.15). For this reason, some studies asked for participants to remove their body hair before the study [1, 4, 27, 38]. However, this could be inconvenient during participant recruitment.

Application of cosmetics on the skin This group of variables is especially important since they influence the radiation emitted by the skin and are difficult to detect. The use of cosmetics, creams, gels or any other type of skin treatment are relevant to the analysis of thermographic images, since they will act as a filter on the skin, distorting its radiation, influencing the emissivity and resulting in an underestimation of the skin temperature [62]. The different studies usually avoid the use of skin lotions or other cosmetic products in the day of the measurement [1, 4, 21, 27].

Physical activity Exercise recovery is a process in which the body works to restore the different physiological processes that occurred in the body during exercise, such as muscle damage, DNA damage, oxidative stress, among others [112, 113]. In relation to the skin temperature, Fernández-Cuevas et al. observed that, after a training session, there is a progressive increase in the skin temperature up to 6 h after exercise [35]. This idea that exercise affects skin temperature a posteriori is an important factor to take into account, and for this reason the studies should request that participants avoid physical exercise on the day of the study [90] and also refrain from high intensity exercise the day before the study [1, 21, 55].

Sunbathing and UV rays The exposure of the skin to sunbathing and UV radiation results in a higher absorption of radiation by the skin, and then in an increase of skin temperature [114]. A good recommendation for the participants in a human thermography assessment is to refrain from sunbathing or from being exposed to UV rays 12 H before the test [21, 30, 56].

3.3 Analysis of the Thermal Data

The analysis process in thermography data still very conservative, as its use in the field of exercise science has only recently begun to grow. Before presenting conclusions from thermal data analyses, there are some important and mandatory steps for proper data analysis.

3.3.1 Qualitative Representation

The thermographic analysis can involve qualitative and quantitative approaches. Qualitative analysis consists of the representation and description of the images obtained. Although a quantitative analysis of the data is fundamental to drawing consistent conclusions, the qualitative analysis is very important for checking whether there is any factor that should be considered in the quantitative analysis. For example, in the qualitative analysis we can see that the assessed person has a varicose vein in the legs and therefore it is very possible that there is a thermal asymmetry. Because of this, it is necessary to always perform a qualitative analysis to ensure the correct interpretation of the numerical data. In addition, this analysis can provide a much faster feedback to the concerned subjects: the athlete, the coach or the medical staff.

Another utility of qualitative analysis is to obtain a graphical representation of what is being evaluated. In this sense, it is important to know the different types of representation currently offered by the thermographic software. Infrared cameras usually have an incorporated digital visual lens that provides interesting visualization tools. Besides the infrared image (Fig. 3.16a), infrared images superimposed

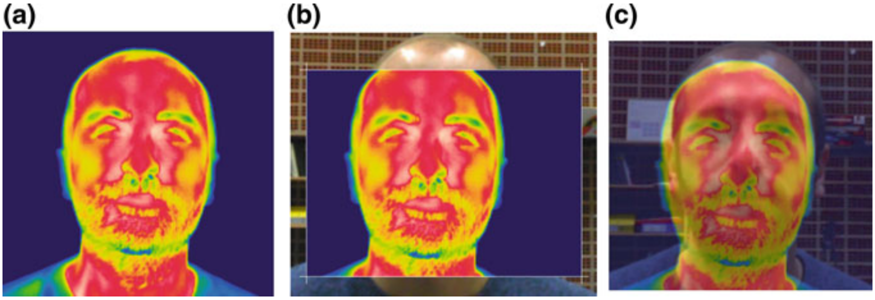

Fig. 3.16 Different thermal image representations

on the visual can also be obtained (Fig. 3.16b) as well as an image that integrates infrared and the visual (Fig. 3.16c). According to the camera, the software, and how both correct the differences between lens in position and other characteristics, the overlap is more or less accurate.

Some of the recommendations usually performed for the qualitative representation of images with humans are listed below [42, 47]:

- Use of a rainbow palette, with white-red as hot and blue-black as cold.
- Use of an image range defined with a minimum of 23–24 °C and a maximum of 36–38 °C. In addition, use of the same image field for all the comparable images b comparable.

3.3.2 Quantitative Analysis

Different variables can be obtained from analysis of the ROI in the thermographic analysis, such as the average temperature, the maximum temperature, the minimum temperature and the standard deviation. In addition, it is possible to calculate other variables such as the variation (Δ) temperature or variation of the skin temperature (difference between before and after an intervention), the thermal symmetry (difference between both body hemispheres) and the Δ temperature of the ROI (difference between the maximum and minimum values). Different studies used different variables for the analysis of thermal images, and there are many still many open questions in this regard. The more common approaches to quantify thermal data are discussed below.

Average temperature is the most used skin temperature variable in the literature [1, 2, 22, 46, 64]. The advantage of using the average of skin temperature in large ROIs is that it can be a representative value and removes the effects of punctual higher values that can be a source of errors. However, when variations are important, the average temperature may not provide the experiment with significant information [30, 55, 56].

Maximum temperature is another thermal variable used in thermography studies [19, 115, 116]. Some previous studies with animals suggest associations between maximal temperature and injury [115, 116], but this needs to be further researched in humans. Related to the maximum temperature is the Tmax method suggested by Ludwig et al. [27], which is described in the Sect. 3.2.1 of this chapter. A positive feature of this method is that, using it, all the ROIs will have the same number of pixels for the calculation, which minimizes the problem of the differences in the anatomical size between participants.

Temperature variation, as produced by exercise, has been suggested as a valid measure for determining the effects of different interventions in studies using repeated measures design [30, 55, 56]. This idea is supported by some studies that observed differences in skin temperature variation after interventions without differences when looking at the absolute magnitudes of temperature [4, 56].

Thermal symmetries were explored in different studies assessing the normal thermal behavior of the participants or the risk of injuries [65, 117, 118]. Vardasca et al. [117] defined thermal symmetry as "the degree of similarity between two areas of interest, mirrored across the human body's longitudinal main axes which are identical in shape, identical in size and as near identical in position as possible". Thermal symmetry assessment is considered a valuable method to assess the physiological normality/abnormality in sport medicine [7, 117], because asymmetries higher than 0.5–0.7 °C are usually associated with a dysfunction in the musculoskeletal system [117, 119, 120].

Δ temperature of the ROI can be an useful measurement for exploring thermal gradients [121, 122]. For example, forearm-finger skin temperature gradient is usually considered to be an index of peripheral circulation and vasomotor tone [121].

Finally, the **mean skin temperature** is the most common variable used in the thermal studies with thermal contact sensors [123]. This variable is determined using different equations and including temperatures from different body regions [123, 124]. There are equations that make the calculations with temperature data from only three regions, whereas other equations that are considered more accurate will need temperature data from up to 15 regions [123, 124]. There is no clear conclusion about how many measurements represents the ideal condition. There are studies showing good results with different numbers of measurements with data from, for example, seven [124] or four [29] measurements. Although this variable is not commonly used in thermography studies, it is possible to measure infrared thermography in the same way, and it can be useful in studies when the main purpose is to obtain an overall value of skin temperature for the whole body.

Other authors suggested that skin temperature should be normalized using the difference between each body regions with one specific body region, rather than considering only absolute magnitudes of temperature [125, 126]. The aim of this normalization is to reduce the variability of the absolute temperatures [125]. Forehead [125] and chin [126] were some of the body regions used as references, probably due to the consideration of these regions as more temperature stable regions.

All of these methods described, in addition to another methods, such as the spectral analysis of the image, need to be investigated in order to elucidate which method is the most suitable for each situation.

3.4 Conclusions

In this chapter, we tried to briefly present the major concerns and implications of selecting a methodology for determining human skin temperature from measurements using infrared thermography. It is possible to note that thermography has many applications in the context of human movement, but more research is needed to determine the adequate procedures for data acquisition and analysis. Furthermore, unlike other techniques for the assessment of human movement, there are significant efforts prior to data acquisition to ensure that the participant will arrive in a condition that minimizes the influence of intervenient factors in the assessment.

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Chapter 4
Infrared Thermography for the Detection of Injury in Sports Medicine

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Abstract In this chapter, we will describe how infrared thermography (IRT) can help us to prevent and monitor injuries, always based on the use of standardised protocols. We will explain some of the main physiological aspects and will enumerate the main applications, with examples gathered from our research and professional experience with top sport athletes and teams. To summarize, IRT can help us to reduce injury incidence and to increase the performance in a non-invasive, fast and objective way.

4.1 Introduction: How Can Infrared Thermography Help Us to Prevent/Monitor Injuries?

Despite the improvement of technology in recent decades, injuries are still a huge problem for professional and amateur athletes and sport institutions. Moreover, injuries are not just a health matter, but also an economic problem for the team or athlete [1], and obviously a factor influencing individual and team performance.

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Nevertheless, we cannot deny the significant and useful changes that new technologies are bringing to sport professionals in order to reduce the injury incidence. One of the key factors is related to the quantification of training loads: internal and external. We speak about a new perspective that has arisen since the advent of tools that help to control the training loads. On one hand, we have the external loads, such as global positioning systems that calculate distances, acceleration, impacts, and so on. On the other hand, we have the internal loads to quantify the biological responses of each individual according to the type of training. In both cases technological tools have been developed to quantify how the athlete is assimilating the training load.

One of the most significant works about the relationship between the workload and the risk of injuries was made by Gabbett and Jenkins in which they identified how the distribution of internal load affect in the incidence of injuries [2]. This study is a milestone in sports science for determining how stimuli affect training in injury prevention. Some years later, Gabbett exposed the fact that the training-injury prevention paradox is based on situation where a training workload control becomes the main tool for injury prevention [3].

In this context, we found different technologies, tools and methods focused on the injury prevention. Among all of them, we identify infrared thermography (IRT) as one of the most interesting technologies for preventing injuries in humans. In recent years, some authors have described how this old technology can be used as tool for injury prevention [4–9].

IRT is a safe, non-invasive and low-cost technique that allows for the rapid and non-invasive recording of radiating energy that is released from the body. IRT measures skin temperature (Tsk) and has been widely used since the early 1960s in different sectors. During the first decades after its development, research into the use of IRT in humans was mainly focused on its applications as a diagnostic tool. However, IRT was replaced by newer and more accurate technologies (such as X-rays and magnetic resonance imaging). Recent technical advances in infrared cameras have made new human applications of IRT (beyond diagnostic techniques) possible. Among others, the prevention and monitoring of injuries has been shown to be one of the most interesting and useful applications because of its ability to identify changes in body surface temperature, reporting on the metabolism of active muscles and monitoring training workload [10].

It is widely known that there is a correlation between muscle activation and the variation of skin temperature [11]. Depending on the type of exercise and intensity, the area adjacent to the muscles involved in the exercise could experience a decrease or increase of the skin temperature, as result of a combination of factors, such as metabolism, muscle contraction, sweating or skin blood flow [12].

Ideally, our skin is supposed to maintain a constant thermal pattern over time, with the constant aim of keeping the body in thermal balance or “homeothermy” [13]. However, a lot of factors can affect the thermal asymmetry of a person during their lifetime, and most of them are related to pathological reasons such as inflammation or nerve dysfunctions [14].

In this sense, IRT can help us to identify thermal asymmetries by comparing bilateral body areas (e.g., left and right knee, or dominant and non dominant calf)

[15, 16]. Thermal asymmetries on those regions of interest (ROIs) may indicate a non pathological pattern (related to dominance factors or ancient injuries or surgeries), but also it could show us a potential injury risk due to an incorrect workload assimilation, excessive activity, asymmetrical exercise execution or muscle overload. Those asymmetries could appear before other indicators as pain, which is extremely useful for implementing preventive strategies before injury occurs. In this way, IRT can be used not only to identify those thermal asymmetries, but above all to identify the reasons for such asymmetry and to modify the training load to come back to the thermal balance.

Moreover, IRT can be also extremely useful once an injury occurs, because we can monitor the thermal asymmetry evolution in order to check if the rehabilitation process is correctly stimulating the areas involved and taking as reference the thermal pattern before the injury [17, 18].

Obviously, there are a lot of factors affecting skin temperature [19], which makes it in some cases impossible to prevent certain injuries. Nevertheless, the frequent record of thermal images allows for an individual comparison of thermal asymmetries over time, providing a reliable database evolution that is a key factor in determining the normal thermal values of a subject, and therefore for individualizing and better understanding any changes to the thermal pattern, and therefore the reasons that may lead to a thermal asymmetry.

To summarize, IRT represents a fast, cheap and useful technique that allows the sport and health professionals to better understand the physiology and health status of a subject. Indeed, if IRT is used following a standardized protocol, with a reliable analysis method or software, and combined with other technologies and the collaboration of different sport professionals, it could really help to decrease the injury incidence [5–9, 20, 21].

4.2 The Protocol: Methodological Aspects and Equipment Requirements

IRT is not a perfect technique. Therefore, the use of a standardized protocol seems to be absolutely essential for ensuring the quality of the thermal results [22].

We are also aware of the differences between using IRT in a scientific context, or facing the reality out of a laboratory. As researchers, we must always try to maintain the protocol quality, nevertheless we should also be able to manage real situations with top elite athletes and institutions where not all the elements are under control, but the results must be still excellent.

In addition to the Chap. 3 of this book, we will enumerate some of the more recognised protocols. Then we will show a synopsis from the TERMOINEF "Protocol for thermographic assessment in humans" [23]. Finally, we will describe the different approaches to analyzing thermal images: qualitative and quantitative analysis.

4.2.1 Thermographic Protocols in the Literature

In recent years, several organisations from the health sector have generated and published their own protocols and quality assurance guidelines. For example, below we list some of the most relevant publications in the last several years:

(a) In 2002, **IACT** published Standards and Protocols in Clinical Thermographic Imaging, which describes some of the basic requirements for performing an accurate clinical assessment with IRT [24].

(b) In 2004, the **International Organisation for Standardisation** (**ISO**) published ISO 9886 focusing on the ergonomic evaluation of thermal strain by physiological measurements [25].

(c) In 2006, Schwartz published a complete guideline prepared by members of the **American Academy of Thermology** (**AAT**) [26]. The guide was aimed at neuromuscular thermologists and other interested parties.

(d) Among the large number of academies, associations and societies, the **European Association of Thermology** (**EAT**) has been one of the most active institutions in recent years in publishing IRT-related studies. The **University of Glamorgan group** (recently renamed South Wales University) has worked to better understand the technical factors that affect IRT measurements and to create a strict protocol for reducing errors and increasing the accuracy and the precision of temperature measurements [22, 27–35]. Ring and Ammer published one of the most cited works regarding the requirements for using IRT in the medical sector [34]. Other authors from this active group have noted important factors in quality assurance [32] or specific applications in fever screening [31]. Most of the works are summarized in the Glamorgan Protocol [29].

(e) Most recently, the research group from the Technical University of Madrid, presented during the XIII EAT Congress in 2015 a "Protocol for thermographic assessment in humans" [23], gathering the most recent updates and results from the research and professional experience of the previous years. The report was reviewed by Kurt Ammer and the EAT scientific board.

To summarize, most thermographic guidelines agree on the following items:

1. Location requirements
2. Equipment characteristics
3. Subject/patient information and preparation
4. Subject/patient assessment
5. Processing and presentation of results.

Regardless of the protocol followed, it is clear that it is absolutely necessary to follow standardised guidelines when using IRT in humans to avoid risking the quality and objectivity of our research or professional work on IRT.

4.2.2 The "TERMOINEF" Thermographic Data Collection Protocol

The TERMOINEF protocol aims to integrate and agree on the most important points with other protocols in the literature [23]. In addition to what was described in Chap. 3, TERMOINEF is a general protocol for taking thermal images with humans, but it has been mainly used in the exercise sector with the aim of injury prevention. Below we will summarize some of the most important points from this and other protocols.

Considerations Prior to the Assessment

Before the assessment, it is highly recommended to have an informative session with the athlete being assessed or the medical staff and professionals involved if they are not familiar with thermography. In this session, which may be physical or virtual, the subjects will be provided with written information, including information about IRT, the processes to be followed during data collection, the type of information to be provided in the final report, and recommendations to be followed before the thermographic session.

We all know that in some institutions and teams, the access to top elite athletes is restricted, but this information should be provided at least to the medical staff so that they could inform them or at least take into account the following factors before the session:

- All evaluations of the same subject should be conducted at the same time.
- No physical activity should be performed for at least 6 h prior to the evaluation (so, ideally before the first training session).
- Avoid the application of creams, gels or sprays on the skin area to be evaluated
- Avoid coffee, alcohol or stimulants for 6 h prior to the evaluation.
- Do not smoke in the 6 h prior to the assessment.
- Do not receive any treatment or massage (it is especially important to coordinate the session with the physiotherapists, so they do not proceed before the evaluation).
- Avoid direct sun or UV sessions before evaluation.
- The previous day (when possible), avoid any drugs or treatment with any substance that may alter the normal thermogram.
- Avoid taking a shower or bath before the evaluation.
- Do not alter rest or meal habits.

In addition to that and since not all facilities are perfectly adapted to data collection, it is highly advisable to visit the location before the day, or with enough time to get it adapted. Sometimes, the only place available is some space in the changing room or near to the place the athletes prepare themselves before the training session. We suggest that it should not occur in a place where the humidity of the showers could change the room temperature and humidity.

Likewise, sometimes the acclimatisation period must be reduced in order to get the most of the athletes assessed. In this case and although some authors have demonstrated the importance of having at least 15 min [36], we prefer to get the thermal images without an ideal acclimatisation period rather than having no measurement. Since we take into account this and other potential influence factors, we can afterwards better interpret the results relating to thermal asymmetries, which are theoretically not that influenced because, in most cases, the factors affect the whole body equally. Standarized protcols are very important and we must try to use them always, but in specific cases (which are common with top athletes), it is better to have the thermal images despite not having them.

Selection of the Camera

We strongly recommend using a thermal imaging camera with a resolution equal to or greater than 320 (horizontal) × 240 (vertical) pixels, a minimum sensitivity of 65 m K, a measurement range covering the possibilities of the human environment (between 0 and 50 °C), a thermal sensitivity of 0.02 °C or lower, and standard data outputs for a PC. The resolution of the camera is one the most important factors for obtaining a high-quality thermal images. A camera with a high resolution will provide a sharper image and a greater number of pixels of the considered ROI, and will improve the quality and reliability of the results.

In recent years, some camera manufacturers have launched low-cost cameras with attractive prices but poor resolution features. Some authors have already analyzed their performance and concluded that they do not have the minimum technical requirements to perform a reliable analysis [37].

Even if it sounds strange, nowadays, most of thermal cameras used with humans are designed and manufactured for other applications, such as industry, security and construction (there is not a specific need to measure 150 °C when working with human skin). However, the potential for sports and human applications for IRT is such a reality that some companies are already working on specific cameras that may be launched by the end of 2016. The more specific they are for human application, the higher the quality of the results will be.

Considerations on the Evaluation Day

On the day of data collection it is necessary to carry out the following steps before starting:

- The first day, the subject should be briefly informed about the characteristics of thermography, the purpose of the data collection and the data details (including anonymity and data processing).
- On the first day, subjects have to sign the informed consent.
- The subject has to undress, staying in underwear (women preferably without bra) for around 10–15 min to acclimate to the temperature of the room, which should be between 18 and 25 °C (ideal: 21 °C).

- During the acclimatization time, we recommend performing a survey with questions concerning the existence of possible influencing factors such as the previous training session, the intake of medicaments, the application of creams or ice on the skin and other influencing factors gathered in the literature [19].

The technician/researcher The person charged with carrying out the evaluation must perform the following tasks before starting:

- To prepare the room at a suitable temperature (between 18 and 25 °C).
- To turn on the IRT camera at least 20’ before (to avoid calibration problems).
- To prepare the tripod (if necessary).
- To locate a step to elevate the subject and isolate the feet from the cold floor. Placing marks on the step will help to standardise the location of the subject’s feet.
- To prepare roll up (if necessary) or make sure to have a proper and non-reflecting background.
- To turn on the weather station.
- To prepare the “black body” or calibration system (if necessary).
- To check with the IRT camera any radiation source in the room (hot pipes, windows, etc.).
- To prepare the notebook with questionnaire data collection for each subject or have a software ready to take those data.
- To turn on the computer, which will be used for transfer and analysis of the photos.
- To check the card or USB drive (or the connection of the camera to the computer) for the data acquisition.
- To turn on the computer, which will be used to transfer the photos and to analyze them.

Camera position This depends on the subject’s height. Normally, it is placed between 2.5 and 3 m (for a subject of 1.70 m height). Regarding the height of the camera, it will be located so that the centre of the image matches the geometric centre of the area to be evaluated (about 65 cm for the lower limbs and 125 cm for the upper body). It is important to keep the IRT camera in a perpendicular angle in relation to the subject. There will be a transparent template to guide the technician on the placement of the subject (see Figs. 4.1, 4.2 and 4.3).

Other protocols, such as the one from Glamorgan [29], have proposed different body views in order to get closer images from the ROIs to be analyzed. Our proposal is based on four thermal images: two from the upper body and two from the lower limb, anterior and posterior views. Obviously, closer perspectives are richer in number of pixels and therefore in objective information, but our proposal is also adapted to specific situations with a lack of time; we can get the whole body from an athlete analyzed with just four images, which is very convenient when we must assess 20 players as fast as possible. We also trust our software analyses and its reliable performance [12] in that the results produced will be good enough to inform decisions and to make a good interpretation.

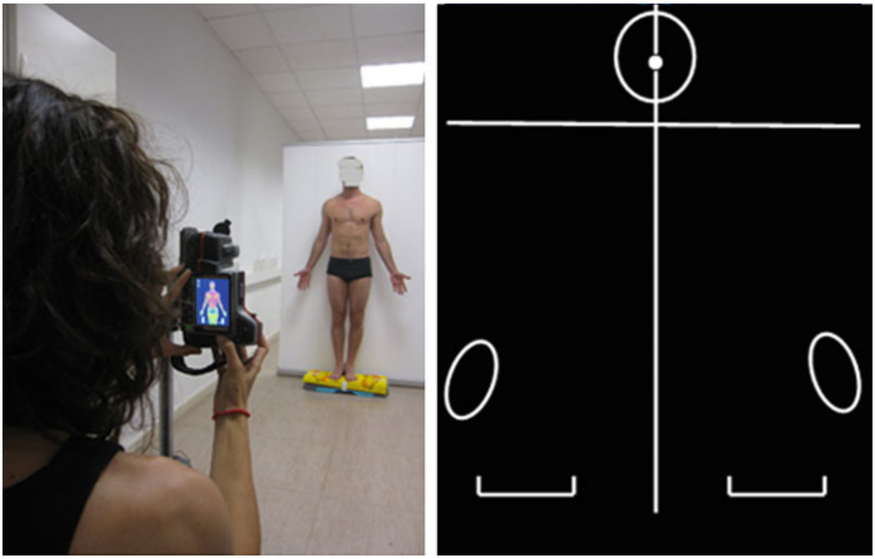


Fig. 4.1 Position of technician behind the IRT camera and transparent template to guide the protocol image record

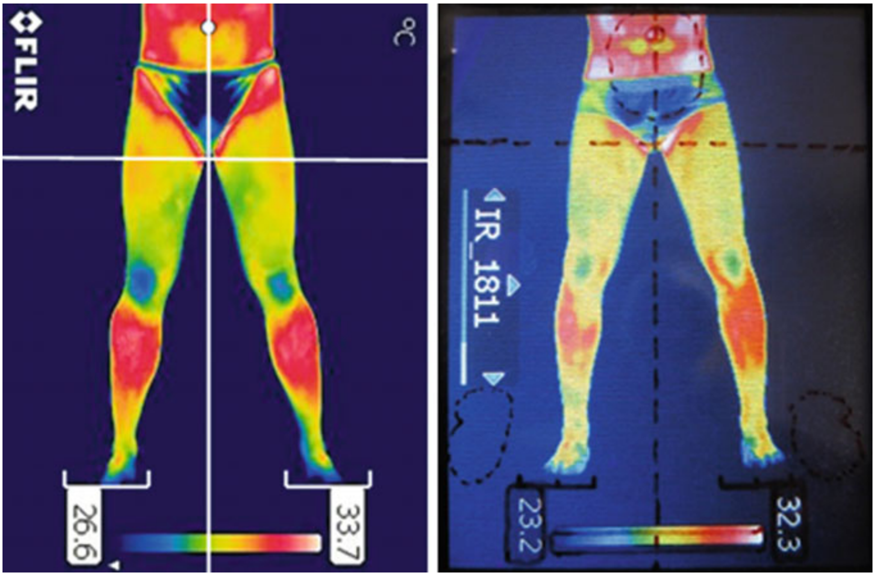


Fig. 4.2 Lower body transparent template reference

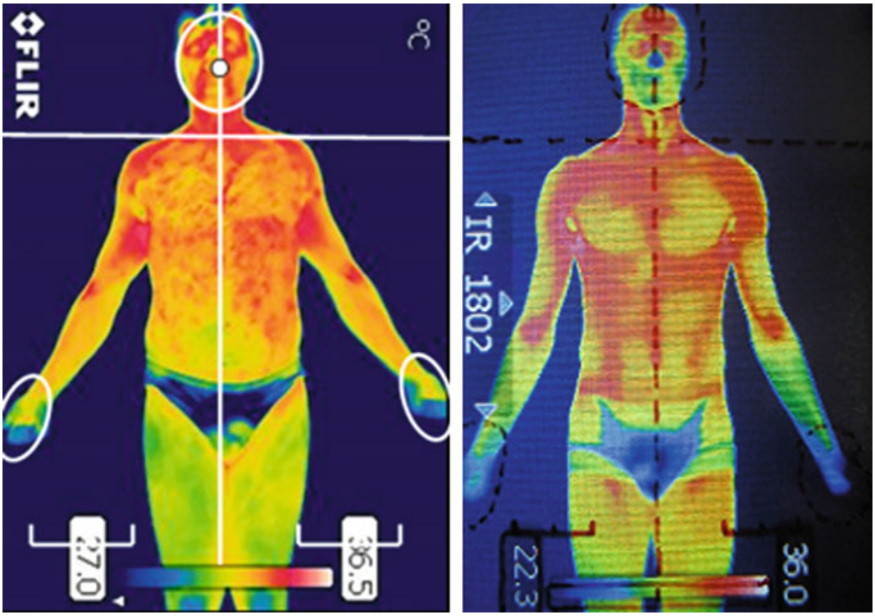


Fig. 4.3 Upper body transparent template reference

During the evaluation Subjects have to follow the following instructions in lower body images (Fig. 4.2):

- The subject stands on a "step" platform to raise his feet (about 10 cm).
- Maintaining an anatomical position (upright and symmetrical).
- Slightly open legs (about 40 cm).
- Feet straight toward the camera.
- Looking ahead.
- Arms crossed or hands behind the head in lower body images.
- Feet must be clearly distinguishable from the background.
- Use of the transparent template as a reference:
  - The lower brands are the places where feet should appear.
  - The crossing of the two lines coincides with the abductors area.
  - The highest point on the vertical line must match the navel.

In the case of upper body images (Fig. 4.3),

- The subject stands on a "step" platform to raise his feet (about 10 cm).
- Maintaining an anatomical position (upright and symmetrical).
- Same leg position.
- Looking ahead.
- Arms relaxed, stretched and slightly supinated so you can see the front or back of the forearm.

- Both hands with fists clenched.
- The head and fists must be clearly distinguishable from the background.
- The transparent template might be used as reference.
    - The temperature bar is just above the knees.
    - The body shape must fit on the image (see Fig. 4.3). That is, the head should be very close to the top edge and the hands to the lateral edges of the image.

4.2.3 Thermal Image Analysis

Once the thermal image is taken, the professional has two main ways to analyze the thermograms: qualitative and quantitative methods.

The quality of the qualitative analysis depends on the experience of the thermographer. The image is interpreted by analyzing the color patterns of the thermograms, and a correct analysis depends on the accurate settings of the camera's temperature ranges. This method can help to identify the most evident asymmetries, but it could be that significant asymmetries are not seen.

The quantitative analysis makes thermography more objective and reliable. It records thermal data (normally maximum, minimum, average and standard deviation) from each ROI by manual or automatic procedures. The thermal results of each ROI can be compared with contralateral or adjacent ROIs of the same subject or with the same ROI of other subjects. In that case, the thermal results for each ROI can be compared with previous thermograms independent of the temperature range settings (Fig. 4.4).

Manual

One of the most controversial points regarding IRT applications in humans is the selection of the ROIs. Many IRT studies have developed their own criteria for creating and selecting ROIs.

The controversy around ROI selection is based on the manual procedure that is required to create ROIs. We observed that the reliability of ICC results (intra- and inter-examiner Correlation Coefficient ICC) were often suboptimal, due to factors that depended on the ability of the observer to manually select the ROI [34, 38]. In some cases of specific thermal images (analyzing closer ROI) it could be appropriated, but the fact that the results will be more difficult to compare with time and with other subjects if the observer is different should be taken into account.

Automatic

To improve reliability and to open up the possibility of comparing IRT results among studies, we suggest the development of automatic and objective procedures to select the ROI. In this sense, software solutions with automatic ROI selection features would be a first step, such as that proposed by different research groups [6, 39–41].

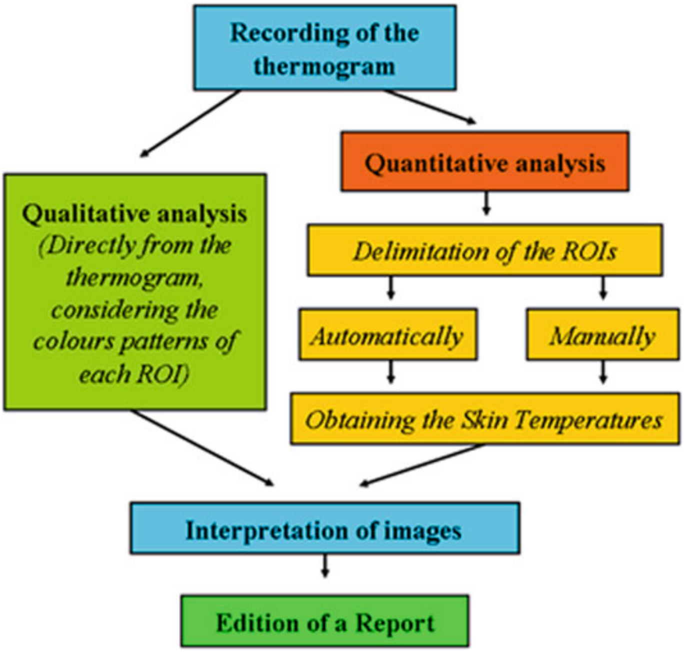


Fig. 4.4 Flow chart of the analysis of thermograms. Figure adapted from Sillero-Quintana et al. [23]

Among all of them, we highlight ThermoHuman. It is a big data Software as a Service (SaaS) online program that uses an applied automatized computer vision solution to obtain human body thermal data. Day-to-day data points are extracted for monitoring thermal asymmetries to help sports professionals in the objective decision-making process and to help avoid injuries. It uses both thermal and personal variables, such as previous injuries, type of sport, dominance, age, height, weight or body mass index, and offers the chance to filter all this information and correlate variables in order to prevent sport injuries.

The ROIs extracted by ThermoHuman allow the professional to obtain the average, maximum, minimum, standard deviation and, of particular importance for data analysis, the number of pixels from each ROI. Currently, there are four protocols that divide the human body in four regions: upper anterior, upper posterior, lower anterior and lower posterior (Fig. 4.5), but more protocols will be developed in the future.

ThermoHuman uses the same procedure than the previous non-commercial version, Termotracker, which was tested with excellent reliability results [12].

We highly recommend performing the thermographic evaluation before the training session. In those cases, it is especially important to get the results as soon as possible, because one of the most interesting advantages of IRT is to obtain fast and objective results that allows the medical and technical staff to take decisions regarding

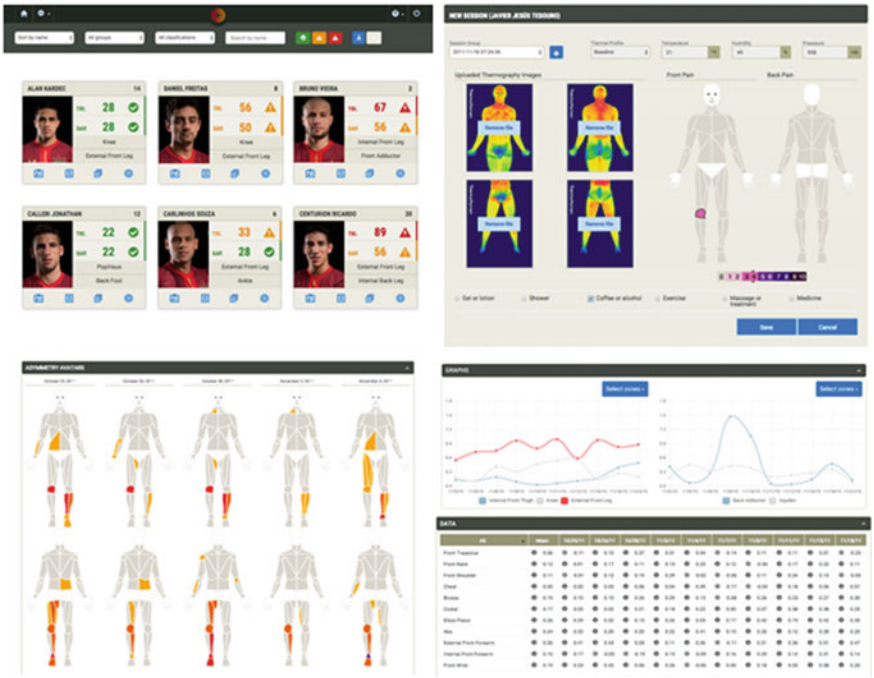


Fig. 4.5 Different interfaces of ThermoHuman software

the adaptation of training if needed, obviously before the session starts. This possibility is only possible by performing an automatic analysis, since manual analysis would not be sufficiently fast to get the outcomes before the training, and, obviously, the results would not be that reliable. In addition to that, automatic analysis helps to compare thermal images of the same subjects or between athletes, so we can get a better and reliable perspective for our athletes and/or team through the time.

Therefore, when using IRT to prevent injuries, it is absolutely necessary to analyze the thermal images with an automatic process (e.g., software) to get more possibilities for preventing injuries or just to adapt the training based on the physical status the athlete.

4.3 The Athlete: Physiology Concepts: From Thermal Asymmetry to Thermal Pattern

In order to understand how IRT can be used, we must describe some aspects related to the subject of physiology. Concepts such as thermal homeostasis and thermal symmetry/asymmetry are the basis for understanding how can we detect injury risk areas.

Another concept worth highlighting is the thermal profile, or the specialization thermal characteristics derived from a sport discipline or concrete performance.

Finally, it is also worth to summarizing the factors affecting human skin temperature.

4.3.1 Biological Principles

Human skin, with an emissivity (an object's ability to emit radiation) of 0.98, is almost equal to a black body radiator [42]. The physics of heat radiation and the physiology of thermoregulation in the human body make the reliable and valid interpretation of thermal images difficult. Skin temperature regulation is a complex system that depends on blood-flow rate, local structures of subcutaneous tissues and the activity of the sympathetic nervous system [43]. However, there is evidence that the sympathetic nervous system is the primary regulator of blood circulation in the skin and is, therefore, the primary regulator of thermal emission [44]. Vasoconstriction and vasodilation of the blood vessels function to regulate blood flow in the skin. Thermoreceptors in the skin, also known as Ruffini corpuscles, recognize the ambient temperature. An increased temperature results in vasodilation, leading to increased blood flow to the skin, whereas vasoconstriction occurs by a decrease in temperature and results in reduced blood flow to the skin [45]. These physiological processes combine with heat transfer and thermoregulation in convection, conduction, radiation and sweat evaporation. Heat transfer by radiation is of great value in medicine [46]. To date, the mechanism of thermoregulatory adaption to exercise is complex and not entirely understood.

Heat exchange between the human body and environment

In the case of the human body, the high metabolic activity generates a great amount of thermal energy, which must be dissipated to maintain the stability of the physiological processes of the body [47]. The mechanisms used by the human body to transfer the calorific energy are: conduction, convection, radiation and evaporation (see Fig. 4.6).

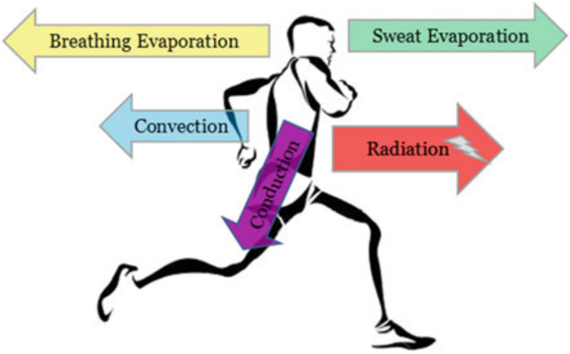


Fig. 4.6 Mechanisms of heat excess release in the human body

The heat transfer by emission and absorption of radiation is called thermal transfer by radiation. We invite the reader to consult Chap. 2 of this book and the work of Incropera [48] or any other literature reference belonging to the field of physics in order to deepen their knowledge about the topic of energy transfer by radiation.

Bodies emit thermal radiation due to their temperature: the higher the temperature, the more thermal radiation that is emitted. However, each material has a different emissivity (see Chap. 2 of this book for emissivity values of different materials).

Emissivity is the ability of each object to emit infrared radiation [49]. Not all objects emit 100% of what they should; if they did so, the infrared signal that would be able to pick up a camera would be directly related to the temperature, according to the Stefan-Boltzmann Law, which relates directly to the energy temperature irradiated.

From the amount of energy dissipated by the human skin, approximately 60% is in the form of infrared radiation [47], and the remaining 40% corresponds to convection. Normally, when working with opaque bodies (as human bodies), the transmissivity is equal to “0”, because the radiation is unable to pass through the body. Consequently, the main concepts in working with radiation and human bodies are the emissivity and reflectivity.

4.3.2 Thermal Homeostasis, Thermal Symmetry/Asymmetry and Thermal Profile

Given that certain physiological disorders may influence the local exchange thermal response [21, 50–52], the use of thermography in sports can help to prevent muscle, joint or tendon injuries since, in cases of overuse or overtraining, the local temperature of the affected areas may be increased, compared with other similar areas or to the contralateral body region [7]. IRT can detect thermal asymmetry that could lead to injury, with its consequent impact on performance and health of athletes, team planning and even, in cases of professional sport or high performance, the economic impact for the athlete or club.

With a periodic thermographic monitoring of the athlete, a specific thermal profile of both the subject and the sport discipline or the team can be created; that is, a “map” with the normal thermal characteristics of each ROI, such as the frontal and posterior legs of a soccer player. Thus, any abnormal temperature rise in both legs or in one specific region, or that takes place continuously or more intensely than normal in an athlete can be related to an inflammatory process [21, 51]. This situation may occur as a result of: a load of training above the assimilative capacity of the athlete, being able to produce a risk of damage by overload; or inappropriate development of recovery patterns, such as balanced nutrition, hours of rest or specific physiotherapy treatments. In any case, it will be necessary to evaluate the cause of the thermal alteration before an injury occurs.

Considering the concept of anatomical proportionality, the thermal response between two contralateral body parts is expected to be symmetrical [53, 54]. Thermal monitoring comparing bilateral body parts indicates that differences up to 0.25 °C [53], 0.4 °C [55], 0.5 °C [15], or 0.62 °C [56] are considered as acceptable. However, differences above these values may indicate that the ROI with a higher or lower temperature, contrasted with the individual's usual thermal profile settings, might have some inflammatory problem (hyperthermia) or degenerative (hypothermia) [21, 51, 55, 57].

According to our research and practical experience, we propose a "level of attention" scale to be considered depending on the bilateral temperature differences recorded (Table 4.1).

Based on the table above showing indications for the level of attention, it should be borne in mind that a difference ≤ 0.4 °C would be considered normal [53–55]. For levels higher than 0.5 °C, the following would be advised: (a) verifying if some external factor could be influencing the result; (b) monitoring the athlete to assess his/her environmental and training conditions; (c) increasing the frequency of monitoring. We never recommend taking drastic decisions after the first negative assessment. In the case that the difference is repeated in the second assessment, an appropriate intervention by the physician, physical therapist or trainer would be recommended, and the intervention should last until the differences come back into an acceptable range considering the normal values of the athlete.

With values classified as "prevention", an immediate decrease in training load or even training suspension is recommended, since when values are higher than 0.8–1.0 °C the existence of a significant inflammatory process [51] or a risk of injury in an ROI is clearly described, even without prior symptoms of pain, and a medical and/or physiotherapy evaluation of the athlete is recommended. The state of "alarm" imposes an immediate suspension of training and a medical and physiotherapy assessment. The "High Severity" status indicates a difference that may be pathological or a sign of major injury; as in other cases, coordination with the medical team is essential to determine the actual state of the athlete.

However, to properly apply the ranges of severity from Table 4.1, we must always consider the individual thermal profile of the athlete and the sport practiced,

Table 4.1 Level of attention scale in terms of the temperature differences obtained between contralateral ROI or between two different measurements of a ROI for the same athlete

Temperature difference	Level of attention
≤ 0.4 °C	Normal
0.5°–0.7 °C	Monitoring
0.8°–1.0 °C	Prevention
1.1°–1.5 °C	Alarm
≥ 1.6 °C	High Severity

since the previous injury of athletes or characteristics of the sport practiced can cause imbalances in the thermal baseline profile that are within normal limits for this specific athlete or discipline, and which could lead the criteria to be applied incorrectly. For example, if the specificity of sport always makes the forearm grip 0.4 °C warmer, it may be normal that one day the athlete has a 0.8 °C imbalance in the forearms, and would not require any special attention.

When significant temperature differences are observed, repetition of the assessment is recommended after 15 min to confirm whether this difference is maintained [55]. Another possibility is to spray the area with an alcohol or convection cooling and wait for five minutes to see the thermal response of the area [55]. This technique is known as dynamic thermography [58].

IRT also allows evaluation of the level of metabolic activity when there is a trauma [21] or after surgery [55]. A regular monitoring during the recovery process allows one to track the evolution of the athlete's thermal profile prior to his/her normal condition before the injury. In addition, the thermographic monitoring allows assessment of whether the medical and physiotherapy intervention evolves as expected.

4.3.3 Factors Influencing the Application of Infrared Thermograhy on Humans

Working with IRT requires taking into account many factors, which could influence either the evaluation or the interpretation of thermal images [38]. Pretending to control such a quantity of factors could entail an "impossible mission", but in many cases, just the knowledge of these factors is a first but important step. Fernández-Cuevas and collaborators published a comprehensive classification of factors that could affect the use of IRT in humans [19]. They divided them into three main groups (see Fig. 4.7).

- Environmental factors: Related to the place where the evaluation is made.
- Individual factors: Those related to the subject assessed and his/her personal characteristics, which could influence skin temperature (Tsk). Those will be divided into intrinsic and extrinsic factors.
- Technical factors: Linked to the equipment used during the IRT evaluation.

As we described in the previous subchapter about protocols, the best way to be aware of the existence of such factors is to use standardised protocols and surveys, so we can note the existence of some of those factors.

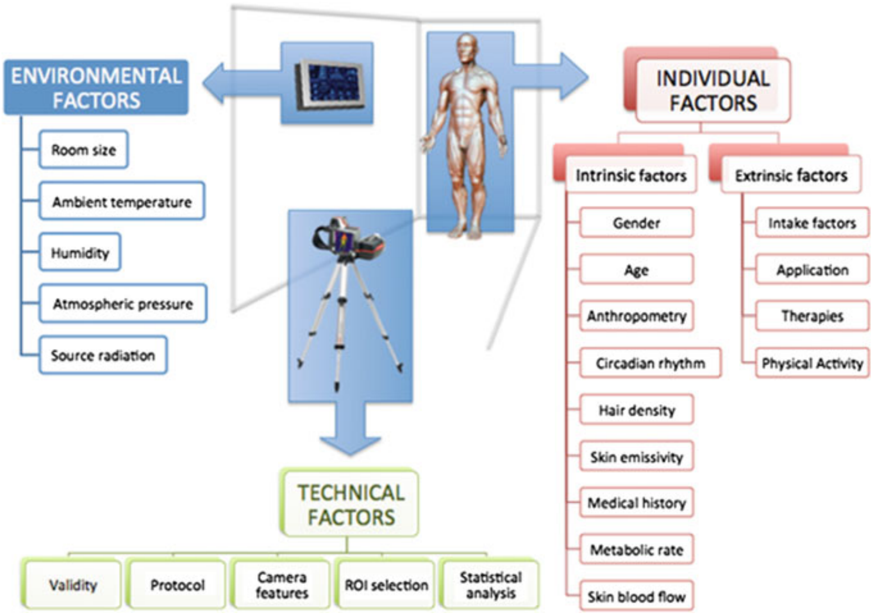


Fig. 4.7 Representation of IRT influence factors classification in humans. Figure obtained from Fernández-Cuevas et al. [19]

4.4 Main Applications of Infrared Thermography in Sport Injury Detection

Physical activity and exercise are one of the most potentially promising IRT applications. Indeed, technological advances in infrared cameras have allowed for a resurgence of investigation in this sector, enhancing new and old applications, such as the following:

- The quantification of training workload [10, 12, 20, 59–61].
- The detection of anatomical and biomechanical imbalances [62, 63].
- The evaluation of fitness and performance conditions [59, 64–66].
- The detection of high temperature risk in pregnant women [67].
- The detection of delayed onset muscle soreness (DOMS) [50].
- The monitoring of fatigue during exercise [68].
- The support in screening and early diagnosis in emergencies [69].
- The evaluation of efficiency levels in some disciplines [66, 70].
- The detection of the lactate threshold [59].
- The monitoring of the respiration rate [71].
- Clothing design and thermal comfort [72–74].
- The prevention and monitoring of injuries [4, 6–9, 20, 21].

Of all those applications, the one focused on the prevention and monitoring of injuries is the one really grabbing attention from researchers and professionals. IRT is able to provide an easy way to record non-invasive and momentary information of the athlete's thermal balance. The objective data given by the thermography expert must be analyzed by the coaching staff (physical trainer, injury therapist, medical staff and coach) in a coordinated way. Therefore, the data will be processed by the sport scientist, who is an expert in thermography and a specialist in research in exercise and sport science and in high performance sport. All of this will positively affect the decrease in the number of injuries and the increase in the team performance, allowing the best players to miss the fewest matches. Based on standardised protocols, IRT will allow us to:

(1) Prevent injuries with the previous training information.
(2) Monitor an injury already started.
(3) Know the answer to the training load.
(4) Have additional information on initial evaluations of athletes.

4.4.1 Injury Prevention

A professional football team has an average of 81 injuries per season [75] and it is expected to have 15 muscle injuries in a 25-player squad [76]. Of those muscle injuries, 92% will impact in four areas: hamstring (37%), adductors (23%), quadriceps (19%) and calf muscle (13%). More than 50% of injuries occur in the muscle and tendon, while two-thirds of them are from muscle fatigue, and the remaining third are from trauma [77]. It is important to categorise the risk depending on the type of injury, the areas that are injured and the total number of days the player misses due to the injuries. Knowing this fact will determine an efficient and concise approach to injury prevention, focusing on areas with the highest incidence and severity.

The use of IRT could save the 7.5 million euros that a Spanish First Division League loses on average due to the injuries [1], if it achieved the reductions of 90% muscles injuries and muscle fatigue in professional football, as suggested by Gomez-Carmona [20]. Then, by continuously monitoring the thermal evolution of the comparison of the dominant and non-dominant members of the football player, we will establish optimal ranges of asymmetry [78] that will allow us to have a standard of care (see Table 4.1, shown in the previous subchapter).

Consequently, when an increase in the thermal imbalance between members (Fig. 4.8) is detected, the technical staff can individualise the training process of that player using the following options:

- Designing specific protocols for the area with asymmetry.
- Reducing the volume of individual work.
- Modifying training tasks to avoid impacting the area with asymmetry.

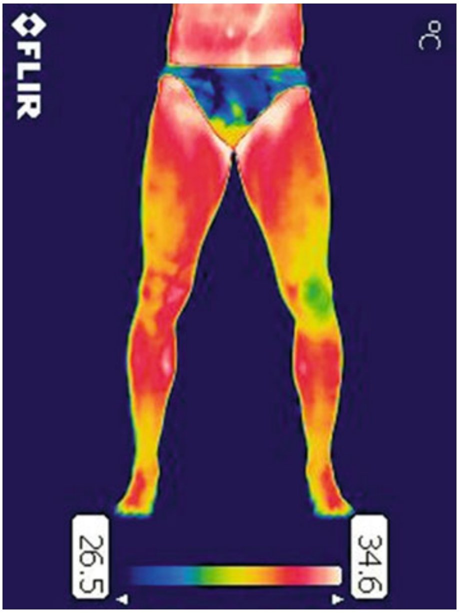


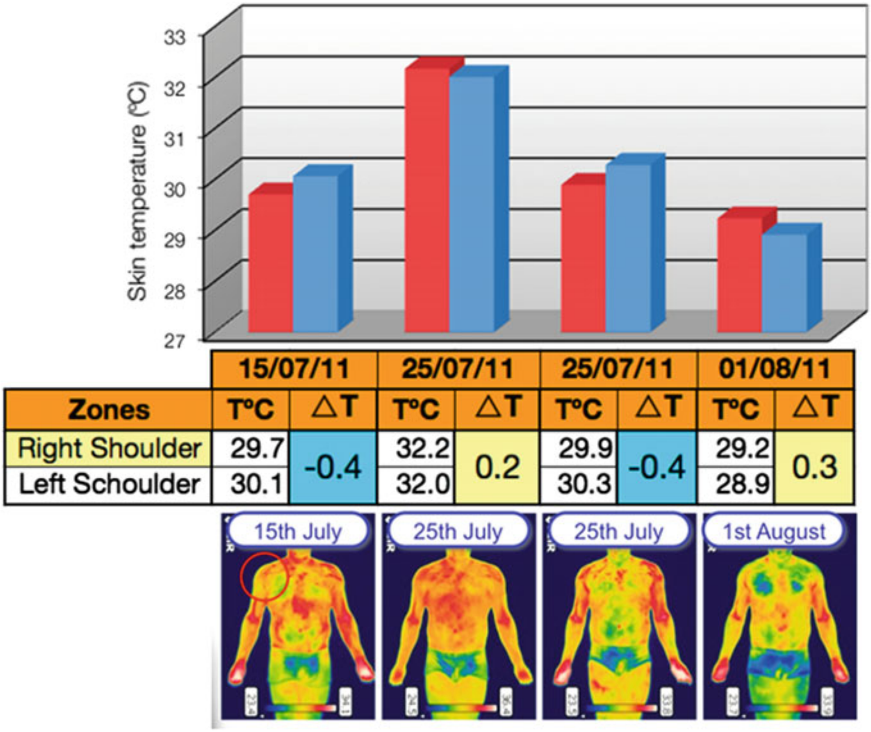
Fig. 4.8 Front view of a football player with a thermal imbalance in the right knee

- Dealing with the physiotherapist.
- No training (giving rest to the player).
- Carrying out additional tests (MRI, X-ray etc.) depending on the severity of the asymmetry.

As mentioned in the previous subchapter, for an optimal tracking of the asymmetries, automatic solutions that quantify the temperature of different ROIs are needed. Using an algorithm for artificial vision, each ROI (muscle areas and/or joint) can automatically be identified and, therefore, comparative reports can be carried out easily between a left–right member or a dominant–non dominant in a scientific way and reliable. This allows us to accumulate and manage the data recorded, establishing thermal evolution of each player, which is essential for assessing individual training load and match response.

One example of how IRT can prevent injuries is the one we experienced with a javelin thrower during our work in Olympiastüztpunkt in Hannover, Germany. We used IRT before starting the physiotherapy session, so we could take the images and analyze them to inform the physiotherapist before he started the session, reporting the main asymmetries.

In that case, the athlete complained about pain in his dominant shoulder. Nevertheless, the thermal images after the training showed a colder asymmetry: his dominant shoulder was 0.4 °C colder than the non-dominant shoulder. We asked him to come before training in order to confirm if this thermal pattern was normal, and before the training, the pattern was different: his right shoulder before training was 0.2 °C warmer. That same day, after the training, the colder asymmetry



	15/07/11		25/07/11		25/07/11		01/08/11	
Zones	T°C	ΔT	T°C	ΔT	T°C	ΔT	T°C	ΔT
Right Shoulder	29.7	-0.4	32.2	0.2	29.9	-0.4	29.2	0.3
Left Schoulder	30.1		32.0		30.3		28.9	

Fig. 4.9 Evolution of shoulder thermal asymmetries (ΔT) on a javelin thrower with pain in his right shoulder (*red bar*). Thermal images were taken after training, excepting the second one

occurred again. Thanks to this information, the physiotherapist could think about a potential nerve compression, and treat the athlete in this way. Hopefully, some weeks after, the pain disappeared and the pattern was different: before and after training, the dominant shoulder was warmer (Fig. 4.9).

Dynamic thermography involves thermal monitoring after a physical stress (cold, heat, exercise) and can be ideal for monitoring possible alterations that are not visible on a daily basis [58]. This technique is often used on the postgame day, involving immersion in cold water that many professional teams perform. In the example of Fig. 4.10, we can observe how the cold stress on the skin temperature is not symmetrical, and therefore we can identify a warmer area around the individual's left ankle. This warmer area could be related to an old injury or area that has been abnormally activated or irrigated. In this case, this thermal pattern was reported to the medical staff in order to follow the evolution and to determine if there could be any dysfunction or problem.

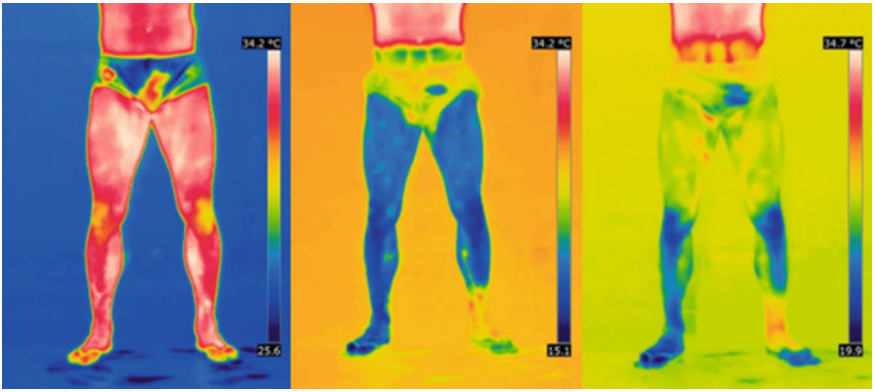


Fig. 4.10 Dynamic thermography after immersion in cold water, where a different thermal response can be seen in an ankle with an old injury that permits a clear recognition of the affected area

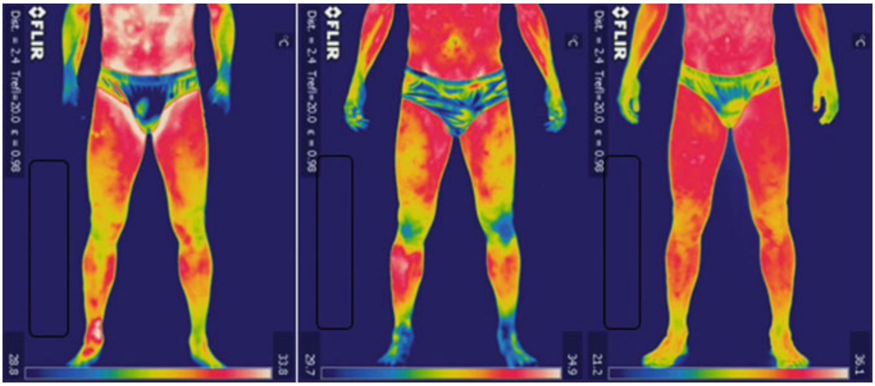


Fig. 4.11 Weekly evolution of a sprained right ankle in a professional football player

4.4.2 Injury Follow-Up

In cases we cannot prevent, when injury occurs, IRT can help in the rehabilitation process quantifying the return to the normal thermal of the player. The degree of asymmetry is recommended for the return to training is still to be defined. For example, it is important to investigate from which thermal asymmetry (1.5 °C, 1 °C or even less) is a player ready to start transition from the process of rehabilitation to training after an anterior cruciate ligament injury operation. This would provide the possibility to individualise rehabilitation and may shorten or lengthen periods in response to the thermal response of each player.

In Fig. 4.11 the evolution of a sprained right ankle over the three weeks of the recovery process of a football player is shown. IRT can help us not just to shorten

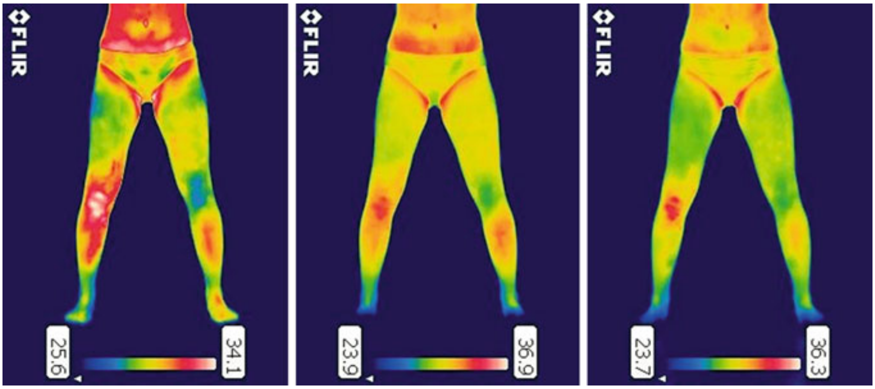


Fig. 4.12 Evolution of an anterior cruciate ligament injury in the right knee of a judoka. From *left* to *right* just after the injury, two months and six months

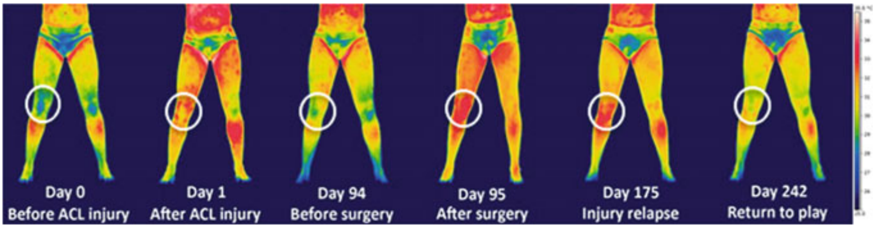


Fig. 4.13 Infrared images of the subject in specific moments from the day before the injury (day 0) to the return to play (day 242)

the recovery process by tracking the thermal asymmetry, but also, to check that the healthy body area (in that example, the left leg) is not getting overloaded and therefore increasing the risk of injury in this area.

Furthermore, Fig. 4.12 shows three stages of evolution of the anterior cruciate ligament injury in the right knee of a judoka with a recovery of several months.

The main problem with thermal monitoring lays in the work of analyzing each muscle area in an isolated way in case there are several injuries that need monitoring. In this case, not only knee cruciate ligament injury, but the response from all the adjoining areas such as the tibial, quadriceps and even popliteal [17]. Therefore, computer applications have been created to automate the identification of muscle areas and extract thermal information referring to each of these areas individually. An example is the software TermoTracker, and its new version ThermoHuman, which identifies 80 ROIs of full body enabling the quick preparation of reports to distribute to the technical or medical staff.

We present an Anterior Cruciate Ligament (ACL) injury evolution in a rugby player: from the day before the injury until the return to play (Fig. 4.13). What makes this case study unique is that during the whole process, the rugby player was monitored by IRT.

Before the surgery (from day 12 to 94), the subject followed a progressive programme five days a week with isometric and concentric exercises to prepare the limb muscles and to maintain the physical condition. After the surgery (from day 111 to 242), the rehabilitation programme consisted of a progressive adaptation to gain range of motion, to reduce the inflammation, to strengthen the muscles, and to gain ability and confidence.

The results can be divided into three phases. Firstly, from the injury to the surgery, we saw a decrease in pain perception and regular ΔT variations, from the biggest (+1.20 °C on day 1) to the smallest difference (+0.08 °C on day 82). Secondly, from the surgery (day 95), we found a similar decrease in the evolution of pain, but a different ΔT_{sk} behaviour, which was maintained during the first weeks of the rehabilitation due to the exercises performed (2). The third phase started some weeks before the return to play (day 175), when the subject again felt a "crack" on his right knee during his first game in a training session. ΔT_{sk} (+1.36 °C) and pain increased but, fortunately, ACL was not torn again. We restarted the rehabilitation, which ended on the 27th June 2012 (day 242) with his first game, and the last one of the season for the team.

In conclusion, IRT results were especially useful regarding the return to play: since Tsk is directly related to the inflammation and muscle activity, it helped both the medical and technical staff to adapt and optimize the rehabilitation process. In addition, the subject described to us how IRT helped him to visualize the evolution, and somehow motivated him to move forward despite the relapse (Fig. 4.13).

4.4.3 Training Load Assimilation

The study of the thermal response to training is one of the most promising fields of IRT. If we are able to predict which areas will be activated depending on the exercise carried out, we will be entering the field of predictive analysis. This thermal information combined with external load indicators such as GPS and internal load indicators such as the subjective perception of the effort or heart rate, can give us a more accurate approach regarding how each individual reacts and assimilate different training loads. It could also help either to predict individual or group response to different training stimulus.

An example would be the realization of high intensity interval training (HIIT), and how its different methods (repeated sprint training, sprint interval training, short bouts or long bouts) [79] impact on one or more muscle areas. If the location and intensity of each of the exercises are known at the thermal level, we will be able to anticipate and individualise what type of training will have less risk for a player.

Observing an explosive player profile that has an asymmetry in the hamstring of more than 0.5 °C. During the training and much more in competition, the player will perform a large number of sprints and a very high percentage of high-intensity running, which increases the risk of injury in the most vulnerable areas, such as the hamstring. Considering the thermal asymmetry in the hamstring area, we should

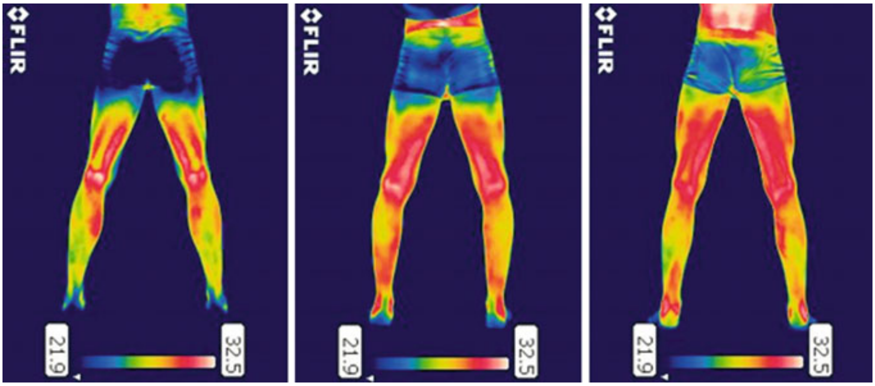


Fig. 4.14 Example of different HIIT protocols on the hamstring temperature in several soccer players of the Madrid highest youth category

avoid HIITs, whose effects can be seen in Fig. 4.14, which increases the effects of the load on that muscle group.

It is not only important to monitor the thermal response immediately after training, but also before starting the session the next day and throughout the week. Sometimes it may appear that residual effects occur, affecting only one of the members, in which localized unilateral temperature patterns are altered (Fig. 4.15) that may constitute a harmful risk if the evolution is not controlled and prevention measures are not taken.

Fig. 4.15 Example of residual effect of workload on the right leg two days after a workout on a football player in Brazil 1st Division

4.4.4 Initial Physical Evaluation

The arrival of a new player to a team involves the medical staff performing a series of tests and evaluations to prove that the player is suitable for physical activity and arrives at the club with a minimum level of fitness. This medical examination includes tests from electrocardiograms to stress tests, but rarely includes tests that reflect vascular alterations as IRT can.

Here is an example of a player in whom a vascular problem was discovered in an initial evaluation in the right lower limb presenting an asymmetry of level four at the knee and thigh. We informed the medical doctor, who transfer the case to the vascular specialist to assess the case and treat the player (Fig. 4.16).

Other thermal changes can also be signs of postural imbalances [62] which, combined with assessments such as tread analysis and manual scan, can increase the success rate in identifying potentially dangerous imbalances for the player.

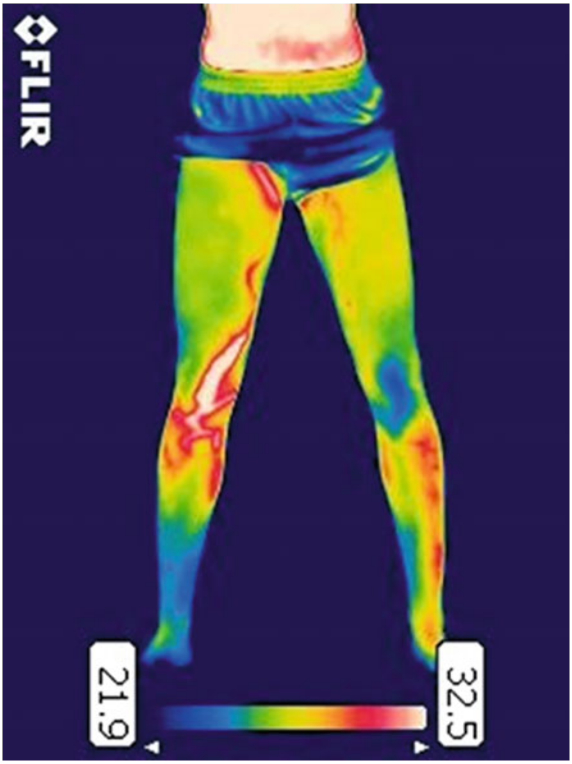


Fig. 4.16 Example of a varicose vein that was located by IRT in a football player on the first thermal evaluation

4.5 Conclusions

IRT has been widely shown to be a tool that can be used by sport professionals with interesting and useful applications. Since IRT is non-invasive, the technology is becoming more accessible in terms of pricing and its results are objective, easy to interpret and fast to get using new software, we strongly believe that IRT will become a commonly used tool, not only by top sport professionals, but also by generic users.

In this sense, our obligation is to highlight the necessity of using IRT with standardised protocols, in order to reduce the influence of factors that can affect the interpretation and results of this technique.

Obviously, IRT is not the final solution for injuries. There is still a lot of research to be performed in order to better understand the human thermoregulation and the skin temperature behaviour. Despite this lack of knowledge, nowadays we can confirm that, based on our research and professional experience in several top sport institutions, IRT is an extremely useful tool to prevent and monitor injuries, and control the individual assimilation of the exercise workload in professional and amateur athletes based on the evolution and asymmetries in skin temperature.

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Chapter 5
The Use of Infrared Thermography in the Study of Sport and Exercise Physiology

Damiano Formenti, Arcangelo Merla and Jose Ignacio Priego Quesada

Abstract Infrared thermography (IRT) is considered an upcoming, promising methodology in the field of exercise physiology. Skin temperature distribution derives from muscular activity, skin blood flow as well as perspiration patterns in specific body parts. This chapter aims to provide a general overview on the literature about the study of the skin temperature response to exercise assessed by means of IRT and its relationship with other thermoregulatory variables, exercise characteristics and performance factors.

5.1 Introduction: Why Is Important to Monitor Skin Temperature in Sport and Exercise Physiology?

At rest, human presents a thermal homeostasis by the regulation of core temperature in values about 36.8 °C [1]. This regulation is managed mainly by the hypothalamus, which receives sensory inputs from central and peripheral sites, and it actives or inhibits the parallel efferent thermoregulatory pathways [2]. However,

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physical exercise and repetitive effort is a challenge to thermal homeostasis [1, 3, 4]. It is well established that physical activity induces complex thermoregulatory processes where part of heat in excess is dissipated through the skin to the external environment [3]. During exercise, the thermoregulatory control of skin blood flow has the fundamental role to maintain normal core temperature and leads to changes in hemodynamics affecting thermal signals [5, 6]. Skin temperature is the result of the heat transferred by the skin blood flow, thermoregulatory responses of heat dissipation such as conduction, convection, radiation and sweat evaporation, environmental conditions, and different biophysical factor such as body surface area or body composition [7, 8]. Therefore, measuring skin temperature provides useful information about the complex thermal control systems.

Research attention has been devoted especially to understand mechanisms limiting performance during exercise in hot and warm environment [4, 9–11]. Among the mechanisms limiting performance during exercise at submaximal intensities in the heat, cardiovascular factors play an important role [3, 9]. Researches have put emphasis on the limitations related to the Central Nervous System (CSN), and the role of high core temperature [9, 12–14]. It has been proposed that high core temperature (~40 °C) would be the primary factor affecting CNS, thus limiting aerobic performance at submaximal intensity [9, 10, 12, 14].

While the increase in core temperature occurs proportionately to the exercise intensity, skin temperature is mainly related to environmental conditions and the heat loss capacity [11, 15, 16]. An increase in core temperature during exercise affects also skin temperature, as heat in excess is transferred from the inner to the superficial parts of the body via cutaneous vasodilation, where is dissipated thorough the skin [17]. Therefore, an isolated increment in skin blood flow accompanies an increment in skin temperature [18]. However, this increment in skin blood flow is commonly accompanied by other processes, such as sweat evaporation. As in many situations, skin temperature can result in a decrease instead of an increase.

However, studies supporting the hypothesis of the critical core temperature were conducted inducing simultaneously high core and skin temperatures [9, 10, 12]. During a lot of time, it was assumed that core temperature was the main responsible of fatigue during aerobic exercise in the heat. However, in the last years this theory has been questioned showing that skin temperature has also an important role, and therefore, the emphasis in research was shifted towards the role of skin temperature [11]. It has been recently demonstrated that the relationship between skin temperature and core temperature, and not only core temperature, has a key role in limiting exercise performance [11, 19]. In particular, critical reduction in the core to skin temperature gradient is the "primary" factor responsible for impaired aerobic capacity, rather than a critical core temperature. [11, 19].

Based on these evidences, in the last years research attention has been devoted on studying the thermal balance between the human body and the environment during exercise through the assessment of skin temperature. During the initial phases of the exercise, skin temperature tends to decrease due to the cutaneous vasoconstrictor response to exercise [20]. After that, skin temperature primarily increases when blood flow shifts from internal tissues to the skin, thus dissipating heat in excess related to an increased metabolic activity [21, 22]. Nevertheless, especially in moderate environments, skin temperature may decrease due to heat dissipation by convection, radiation and evaporation [23, 24].

All in all, skin temperature in specific regions of the body is the result of a thermal balance between muscle activity, vasodilation and sweat evaporation [3, 24].

This chapter aims to provide a general overview on the literature about the study of the skin temperature response to exercise assessed by means of infrared thermography (IRT). More specifically, the chapter is made in order to provide the reader with an understanding of the effect of exercise on skin temperature. Specifically, some important factors that affect the behaviour of skin temperature during exercise and sport will be presented and discussed, as well as some of the most significant studies on infrared thermography to date. In order to fulfill all the above points, the chapter is structured as follows:

1. First, the chapter will discuss some methodological issues that could affect the skin temperature behaviour during exercise, such as the instrument used (e.g., thermal contact sensors or IRT) as well as the characteristics of the exercise.
2. Second, the chapter will show the relationship between the skin temperature and other thermoregulatory variables (i.e., blood blow, core temperature and sweat rate).
3. Third, the chapter will review the effect of the exercise on skin temperature in relation with different experimental and exercise conditions.
4. Finally, the chapter will show the relationship between skin temperature and performance variables (VO_{2max}, heart rate, neuromuscular activation and body composition).

5.2 Measuring Skin Temperature in Exercise Physiology: Methodological Aspects

5.2.1 Measurement Instrument: Contact Thermal Sensors Versus Infrared Thermography

Typically, skin temperature is measured using contact thermal sensors, such as thermocouples or wired thermistors, usually considered as gold standard methods (despite its limitations, as this section will show). A thermocouple is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more joint locations. Their system is based on the Seebeck effect, which occurs when a difference in electric potential is created between two conductor materials at different temperatures [25, 26]. Thermistors are resistors in which resistance varies with temperature, allowing stored calibration data within the circuit to convert this to a temperature value. Thermistors and thermocouples are non-invasive, but the associated wiring requires familiarisation and a hard-wired connection to a computer, thus making difficult skin temperature monitoring during dynamic conditions, such as during dynamic movements [27].

In recent years, thermocouples have been also developed in wireless system, providing a solution to the limitations of hard-wired methods. In fact, wireless sensors provide subjects with great mobility as they do not interfere with their movements, such in case of physical exercise during high dynamic situations, both in laboratory and in the field [26, 28]. These sensors allow also measuring below or in-between clothing layers [29].

Although contact thermal sensors presents some advantages, there are some limitations in its use. 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 [30]. Furthermore, thermal interactions between contact sensors and environment can affect the reliability of the measurements [26]. Contact sensors are usually attached to skin using different types of clinical tapes. The attaching method of contact sensors to the skin has been shown to affect the local heat transfer [31, 32], thus influencing the local thermal regulation and skin temperature [28, 33].

An alternative device to measure skin temperature is IRT. IRT has become popular in the last years in sport and exercise physiology research due to its non-contact and non-invasive character. Furthermore, IRT obtains a thermal image, which can measure the temperature at all points, thus allowing to measure large areas instead of single points (such as contact sensors) [28, 30]. As can be seen, IRT can solve some of the limitations of contact sensors. For this reason, apart from studies applying IRT in the measure of skin temperature modifications related to exercise, in the recent years research attention has been devoted also to investigate the validity of IRT against thermal contact sensors during both resting and exercising condition [27, 28, 30].

De Andrade Fernandes et al. [28] published a study aimed to compare the mean skin temperature measured using thermocouples to those measured using IRT and to check the agreement between the two methods before, during and after exercise performed in thermo-neutral environment. Two identical experimental protocols were performed in two different days, one with the thermocouple measures, and one with the IRT measures. In each of the two days, the subjects completed an interval test on a treadmill consisting of 12 blocks of 5 min, each one separated by an interval of 1 min, during which temperature was measured. The exercise intensity was individually fixed to 60% of the VO_{2max} speed obtained in the pre-session experiment.

Low agreement between the mean skin temperature values measured using thermocouples and IRT was found in each of the three phases considered (before, during and after exercise), demonstrating the discrepancies between the two methods. Thermocouples showed higher mean skin temperature values during exercise than IRT, while IRT showed higher values before and after exercise. The results indicated that the interpretation will vary depending on the method employed (Fig. 5.1). The authors suggested that the low agreement between

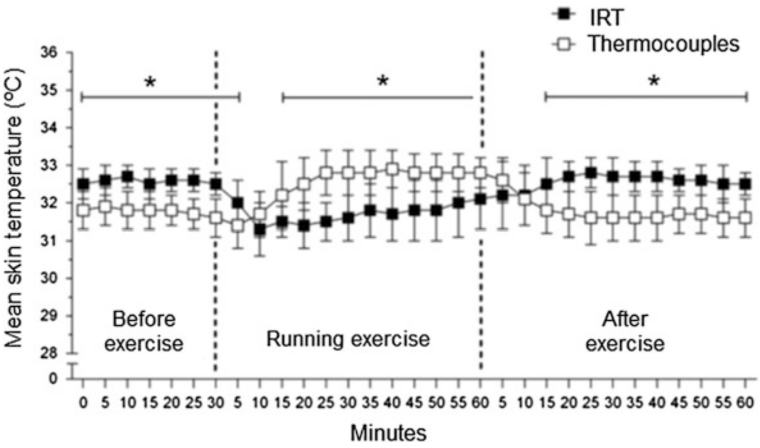

Fig. 5.1 Mean skin temperature values pre-, during and post-exercise obtained from thermocouples and IRT. Significant differences between methods are shown using *. Figure modified from de Andrade Fernandes et al. [28]

thermocouples and IRT could be mainly due to the contact character of thermocouples. In fact, several factors could contribute to explain the observed differences: the pressure exerted by fixation methods and the use of substances for the fixation [33]. Furthermore, increased heat loss by convection and evaporation in those regions where thermocouples were fixed could contribute to increase the mean skin temperature measured by thermocouples [31, 33].

Another study investigated the agreement between hard-wired thermistors, telemetry thermistors (i.e., wireless sensors), and IRT during exercise in a hot and humid environment [27]. Subjects performed an incremental running exercise test in a climatic chamber with an environmental temperature of 31.9 ± 1 °C and relative humidity of 61 ± 8.9%. Skin temperature was measured at four different sites (i.e., chest, arm, thigh, calf), and mean skin temperature was computed with the weighted average: chest 30%, arm 30%, thigh 20%, and calf 20% [34]. Exercise started with speed between 8 and 10 km h^{-1}. Each subject completed five stages of three minutes, with speed increasing by 1 km h^{-1}. At the end of each stage, subjects straddled the treadmill and the thermal camera recorded skin temperature at each site. The authors concluded that IRT tended to under-estimate the temperature values measured by hard-wired thermistors. Authors suggested that the differences between methods could be due by the contact and fixation of the thermistors as in the previous study, but mainly by a measurement error of IRT due to the alteration of the skin emissivity by the sweat. Due to this interpretation, the authors suggested that IRT may be a useful tool for measuring skin temperature in static and controlled environments, but its use is not recommended for live monitoring during dynamic conditions, such as during exercise.

More recently, another study compared IRT and thermal contact sensors for measuring skin temperature in various parts of the body in a moderate cycling scenario and subsequent cooling down phase [30]. Furthermore, the novelty of this study is that the authors compared the results of human scenario with a more controlled scenario: surface temperature of a hot plate system during dry and wet conditions. This instrumented test was conducted to exclude human thermoregulatory processes when simulating heat exchange in dry and wet conditions. The exercise test protocol was structured in the following phases and is resumed in Fig. 5.2:

1. Thermal adaptation phase (15 min): Standing in the laboratory. The investigator attached the skin temperature sensors within the first minutes of this phase. Thermal images were recorded at the end of this phase (Pre-cycling).
2. Cycling phase (48 min): After warming-up for 3 min at 50 W and 90 rpm, participants cycled at 50% of their maximal power output at 90 ± 3 rpm. Thermal images were recorded immediately at the end of the exercise (Post-cycling).
3. Cooling-down phase (10 min): Standing in the laboratory. Thermal images were recorded at the end of this phase (Post-cooling).

Immediately after cycling, IRT provided lower temperature values with respect to thermal contact sensors, whereas it presented higher temperatures after the cooling-down phase [30]. In the exercise trial, the correlation coefficient between the two methods was high when measured before cycling ($r = 0.92$) whereas it was reduced immediately after cycling ($r = 0.82$) and after the cooling-down phase ($r = 0.59$). However, the discrepancies in temperature between the two methods remained within the accuracy of the thermal camera (±2 °C). Comparable results were observed between dry and wet states when comparing exercise test and instrumented tests, in which no water coating was present, suggesting that in such exercising scenario, sweat delivery was not high enough to produce a continuous water layer on the skin. Furthermore, they suggested that the comparable differences between the instrumented test and the human scenario are showing that differences between both methods are mainly related to the effect of the contact sensors on the reduction of heat loss (via radiation and sweat evaporation). The authors stressed that these findings demonstrate the possibility of using IRT in the field of sports and exercise physiology for assessing skin temperature.

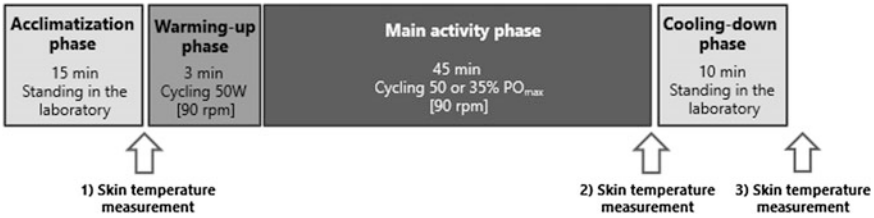

Fig. 5.2 Experimental protocol of the study (PO$_{max}$ corresponds to the peak power output if pedaling at 90 rpm determined in pre-test). Figure adapted from Priego Quesada et al. [30]

Based on the findings of these methods-comparison studies, IRT seems to be appropriate for measuring skin temperature modifications associated to exercise. IRT allows to measure skin temperature distribution with high sensitivity (0.05 °C), thus having the main advantage to be capable of analysing large and thus, more representative areas on the body surface. Due to its non-invasiveness, heat transfer process at skin level is not affected by attachment of sensors. Nevertheless, thermal contact sensors have some advantages with respect to IRT, especially when measuring absolute temperatures in particular setting conditions. For example, contact sensors have the possibility to measure temperature when subjects are clothed, or when body posture and space do not allow having optimal conditions to record infrared thermal images [30]. Furthermore, sweat on the skin produced during and after exercise may act as a filter for infrared radiation and that could lead to an error in the estimation of the skin temperature using IRT [35]. However, this issue needs future studies to explore the real physical effect of the sweat on the calculation of skin temperature using IRT in the different exercise scenarios.

To conclude this section, it is important to take into account that advantages and disadvantages of both methods should be considered before designing a study assessing skin temperature changes associated to exercise, and cautions should be taken to control possible sources of error. Furthermore, it is important to consider the measurement method during the interpretation of the result of one study.

5.2.2 Exercise Characteristics and Experimental Approach

In the last decades, many authors have described the skin temperature response to exercise in different body areas under different conditions and different experimental approaches [16, 36–42]. Although drawing a certain conclusion on the skin temperature response to exercise seems to be difficult due to huge discrepancies between studies in aim and methodology, it is generally accepted that skin temperature modification associated to exercise—and its physiological meaning—varies in relation to several factors. Among them, the most relevant are characteristics of the exercise and different experimental approaches.

In general, exercise can be classified on the basis of the discipline (i.e., the type of discipline studied, such as running, cycling, or specific resistance exercise). For example, Merla et al. [40] investigated the skin temperature response to running exercise, as well as Priego Quesada et al. [41] did for cycling exercise. However, in the case of resistance exercise, it is important to distinguish between singlejoint resistance exercise and multijoint resistance exercise. Singlejoint exercises usually isolate a specific muscle or muscle group (such as leg extension), whereas multijoint exercises usually recruit one or more large muscle groups as agonist muscles (such as squat), and other muscles as coacting muscles (for example for stabilization). Most sport activity and daily movements consist of multijoint movements. The more similar the training activity to the actual sport and daily movements, the greater positive transfer of resistance exercise to these movements (i.e., the specificity concept). In general, from both scientists and practitioners point of views, multijoint exercises are considered more suitable for improving sport and daily performance with respect to single-joint exercises [43]. The fact of recruiting single muscle group (singlejoint exercise) rather than large muscle groups (multijoint exercise) is likely to differently influence thermoregulatory processes (especially vasoregulation), thus in turn to influence also skin temperature response to exercise in different way. As regards to the study of the skin temperature response to singlejoint and multijoint exercises, both are present in the literature. For example Formenti et al. [39] studied the skin temperature response of anterior thigh to a typical multijoint exercise, such as squat; on the other hand, Ferreira et al. [37] investigated the skin temperature response on posterior thigh to a single joint exercise (knee flexion).

Furthermore, it has been shown that skin temperature response varies according to the intensity and the duration of the exercise. For example, Balci et al. [36] examined the difference in the skin temperature dynamics during a submaximal constant load cycling exercise and a maximal incremental cycling exercise. It was found that the skin temperature time course during the two trials exhibited a different dynamic. On the other hand, Priego Quesada et al. [16] assessed the effect of different cycling workloads on core and skin temperature. They observed that cycling workload did not have any effect on the skin temperature in the almost totality of the body regions due to the higher heat loss of the thermoregulatory system, and only Regions of Interest (ROIs) that are mostly constituted by connective, bone and fat tissues were affected (Fig. 5.3). These ROIs presented higher reductions of the skin temperature at the higher workload (50%). The authors suggested that these regions, that are not located on top of active muscles, are affected by a temperature decrease due to a higher overall sweat rate according to a higher intensity, rather than temperature increases through rising workloads. On the other hand, core temperature increased continuously throughout the exercise, as expected.

Investigations have been conducted with the aim to study localized effect of the exercise, or systemic effect of the exercise. These are different experimental approaches, which are both present in the literature. For instance, Zontak et al. [42] measured the skin temperature response of hands before, during and after two bouts of cycling exercise. In this study, while the cycling exercise involved only lower limbs, the skin temperature was measured on the hands. Thanks to this approach, the authors were interested in studying the systemic effect, since the skin temperature was measured over parts of the body not involved in the exercise directly. Another experimental approach was used by Formenti et al. [38], which compared the skin temperature response to standing calf rise exercise in a sample of trained and untrained subjects. In this paper, the authors aimed to study the localized effect of the exercise, since skin temperature was measured on the calves area of the subjects, i.e., the muscle tendon unit directly involved in the exercise movement. A simultaneous evaluation of systemic and localized effect is also possible since both measurements can be combined in the same study. For example, Priego Quesada et al. [16] investigated the influence of cycling workload on core and skin

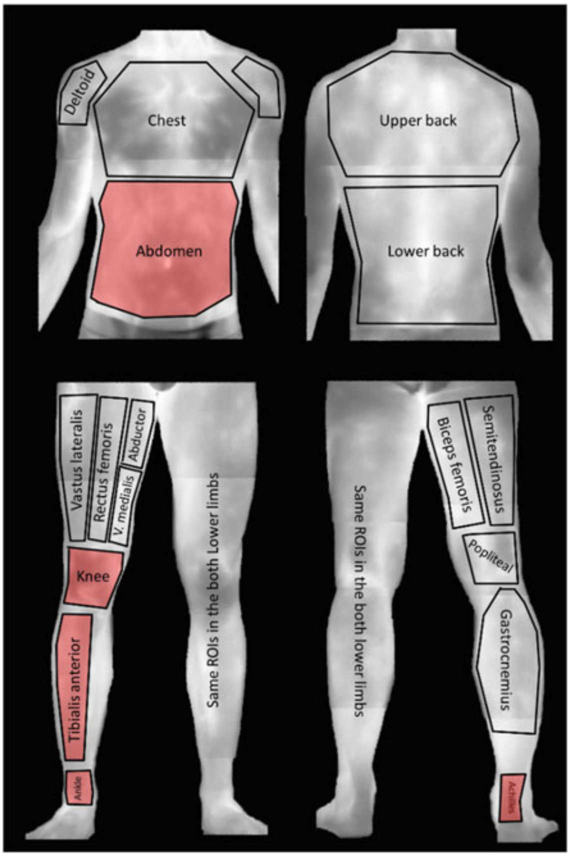

Fig. 5.3 ROI representation of the differences in the variation of skin temperature between 50 and 35% PO_{max}, using a red background in the ROI, in the study of Priego Quesada et al. [16]

temperature measured in seventeen different regions of interests on lower limbs (i.e., over the muscles involved in exercise) and on the trunk.

Moreover, the experimental approach is different when researchers are interested in studying the dynamic of the skin temperature time course during exercise, or when researchers are interested in a pre-post exercise comparison of skin temperature. These are different methodological approaches to the problem, with different physiological meanings. Merla et al. [40] measured skin temperature of various parts of the body continuously during running exercise using a sampling rate of 50 Hz. The authors were clearly interested in studying the dynamic of skin temperature changes occurring throughout the duration of the exercise. Conversely, a pre-post comparison approach was used by Priego Quesada et al. [41], which investigated the relationship between neuromuscular activation (measured using surface electromyography) and skin temperature (measured using infrared thermography) during cycling exercise. In this study, three thermographic measurements were performed in different moments of the experiment: before the cycling test, immediately after the cessation of the cycling test, and 10 min after the cessation of the cycling test. This approach is usually followed by a type of analysis considering the skin temperature variation, as follows [16, 41]:

- ΔT: Difference between temperature immediately after the cycling test and before, expressed in °C.
- ΔT_{10}: Difference between temperature 10 min after the cycling test and before, expressed in °C.
- ΔT_{after}: Difference between temperature 10 min after the cycling test and immediately after, expressed in °C.

All in all, among the variables influencing skin temperature modifications associated to exercise, exercise characteristics and experimental approach are probably the most relevant, and those that researchers should be aware when designing experiments.

5.3 Relationship of Other Thermoregulatory Variables with Skin Temperature During Exercise

Skin layer constitutes the interface between the human body and the external environment. It plays a fundamental role in thermoregulation processes, thus regulating heat transfer produced by metabolism between the core to the external thermal conditions of environment [44]. Modifications of skin temperature are primarily modulated by skin perfusion, which is a function of microvascular anatomy and vasoactive control of the autonomic nervous system [2, 5]. Under conditions of hyper thermic stress, skin blood flow can be regulated, thus increasing in the skin surface for transfers of heat from the body, and the sweat rate increases to dissipate the heat from the skin to the environment [2]. Conversely, under cold environments, cutaneous vasoconstriction is produced and the skin plays the role of insulating the body from external environment [2].

Infrared imaging provides a visual map of the skin temperature of the body surface. However, it is worth noticing that an infrared image cannot quantify measurements of skin blood flow. The infrared image provides a map of temperatures of the skin, which in turn is a function of blood perfusion to the surface area [45]. Nevertheless, thermal changes on the skin may also be influenced by external thermal stressors. Therefore, skin temperature is the result of a complex interaction between skin blood perfusion, environmental temperature, heat loss processes and biophysical characteristics [7, 8].

The process of repeated and/or sustained contraction of the muscles during an exercise bout produces heat, leading to an increase in body temperature [21, 46]. Therefore, during exercise thermoregulatory reflexes are activated with the aim to reduce body temperature, and to maintain thermal homeostasis [2]. Cardiovascular system during periods of exercise aims to provide sufficient amounts of oxygen and nutrients to the active muscle [3]. To this purpose, as exercise begins, muscles involved in exercise rapidly require increased oxygen delivery. This need is mediated by the sympathetic stimulation of vessels in those areas where blood flow can be recruited (e.g., splanchnic and renal circulations), thus increasing blood flow in the exercising muscles. Meanwhile, thermoregulatory reflexes, aiming to reduce body temperature, lead to an increase in skin blood flow [2]. Therefore, thermoregulatory reflexes induced by the thermogenic effect of the exercise are in conflict with non-thermoregulatory cardiovascular responses to exercise [20]. For instance, during intense exercise and/or during exercise in warm environment, there is a competition between thermoregulatory and non-thermoregulatory reflexes. The first for increasing blood flow to the skin, the second for increasing blood flow to the active muscles. In general, these competing demands are resolved thanks to the increase in cardiac output [3]. However, increasing cardiac output may not be enough to resolve deficits resulting from combined intense exercise and heat stress (also when the dehydration is present), thus possibly leading to cardiovascular collapse [3].

The sympathetic control of skin blood flow is unique as there are sympathetic vasoconstrictor fibers (similar to those present in skeletal muscles) and sympathetic active vasodilator fibers in the skin surface. During exercise, as body core temperature rises, there is an initial vasoconstriction response caused by the increased demand of blood flow to the active muscles. However, once a specific body core temperature threshold is reached, skin blood flow begins to increase by the activation of the sympathetic active vasodilator response. Such increase in skin blood flow during exercise aims to promote heat loss, because blood flow is the first mechanism of heat transfer from the inner part of the body to the skin. Therefore, an increase in skin blood flow is likely to accompany an increase in skin temperature when sweat evaporation is not present.

Acute thermoregulation adaptations to exercise have been extensively studied by monitoring skin blood flow [6, 47, 48]. However, exercise is associated with large hemodynamic responses involving a series of thermoregulatory processes. Since exercise causes heat production within the body and invokes cutaneous thermo-regulatory processes, modifications of skin temperature associated to exercise can be monitored by infrared thermography. Recent studies have investigated the interaction of skin temperature measured by thermography with other variables influencing thermoregulation in response to exercise. Three studies will be presented and discussed briefly [16, 39, 40].

Priego Quesada and colleagues [16] investigated the relationship between core and skin temperature measured in different sites of the body. Fourteen cyclists performed two 45-min cycling tests at 35 and 50% of peak power output on different days, with a constant cadence (i.e., 90 rpm). Core temperature was measured using an ingestible pill continuously throughout the test. Local skin temperature was recorded using infrared thermography before, immediately after, and 10 min after the end of the cycling tests. In general, from pre to post exercise skin temperature decreased in trunk regions, whereas increased in lower limb regions. Core and local skin temperatures showed moderate negative correlations for regions presenting the highest sweat rates over the body (such as trunk) whereas some positive correlation were observed in regions in which sweat production was low (lower limbs). These findings highlight the difficulty of finding a relationship between skin temperature and core temperature, probably due to the thermoregulatory system efficiency in the increase of the thermal gradient (i.e., the difference between core and skin temperature) [11, 19], together with the multifactorial nature of the skin temperature [8, 30].

In another paper, Formenti and colleagues [39] studied the skin temperature response to two types of resistance exercises modulating the amount of skin blood flow. The rationale was that low intensity resistance training with slow movement and tonic force generation has been shown to create blood flow restriction within muscles (and therefore an important muscle de-oxygenation), thus maximizing the hypertrophic response even with low intensity. This condition of restricted muscle blood flow may affect skin blood flow, and in turn thermoregulation through the skin. Therefore, the authors investigated the effect of two speeds of exercise execution on skin temperature dynamics using infrared thermography. Thirteen active males performed randomly two sessions of squat exercise (normal speed, 1 s eccentric/1 s concentric phase, 1 s; slow speed, 5 s eccentric/5 s concentric phase, 5 s), using ~50% of 1 maximal repetition. Thermal images of skin temperature of the muscles quadriceps were recorded before the exercise (to determine basal skin temperature) and for 480 s following the initiation of the exercise (to determine the non steady-state time course of skin temperature). In summary, this study showed that squat exercises performed at two different speeds (1 s vs. 5 s) until exhaustion determined different profiles of skin temperature of the muscles quadriceps. Although the two exercises determined comparable maximal excursions of skin temperature, the rate of change of skin temperature was strongly reduced during the 5 s exercise as compared to the 1 s exercise (Fig. 5.4). Since the 5 s exercise mimicks a condition of blood flow restriction within the muscle, these data provided a detailed portrait of the skin temperature modifications associated with this condition, thus laying the basis for similar investigations using IRT coupled with Doppler flowmetry.

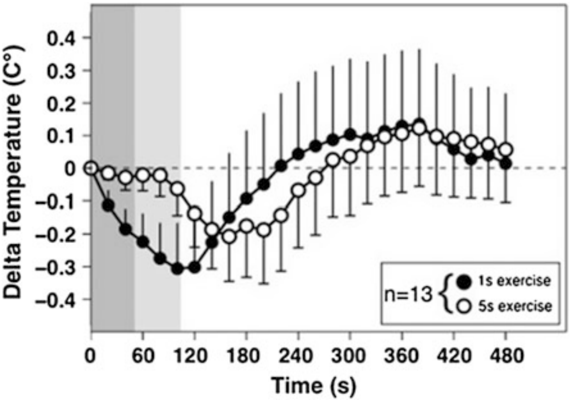

Fig. 5.4 Skin temperature variation from baseline recorded during 1 s exercise and 5 s exercise speed of a squat exercise. *Dark grey* and *light grey bar* represent the mean duration of 1 s exercise (55 s) and 5 s exercise (100 s), respectively. Figure obtained from Formenti et al. [39]

In the study by Merla et al. [40], the authors investigated the whole body anterior skin temperature modifications in well-trained subjects during an incremental running test until exhaustion. Fifteen males volunteers performed an incremental treadmill test until reaching their individual maximal heart rate. Skin temperature of total body was continuously monitored by infrared thermography. Skin temperature decreased as the subjects began the exercise, whereas a further skin temperature decrement occurred with the progress of the exercise. This was attributed to the continuous vasoconstrictor response, attributable to an increase in catecholamine and other vasoconstrictor hormones released as the exercise intensity increases [49, 50]. Thighs and forearms exhibited the earliest response. At the exercise interruption (i.e., at exhaustion), skin temperature values were 3–5 °C lower with respect to the baseline, and began to increase during recovery. Thighs and forearms exhibited the faster increase, followed by the total body skin temperature increase. Thermal images documented the presence of hyperthermal spots due to the presence of muscle perforator vessels during recovery (Fig. 5.5). The diffusion of heat from the hyperthermal spots to the surrounding cutaneous tissue suggests a possible hemodynamic and thermoregulatory role for the perforator vessels during/after exercise [51]. The findings of this study indicate that infrared thermography permits the quantitative evaluation of acute cutaneous whole body thermal adaptations occurring in response to an incremental exercise until exhaustion. It is such an incremental character of the exercise that caused a continuous vasoconstriction response, thus requiring blood flow to the active muscles from the other parts of the

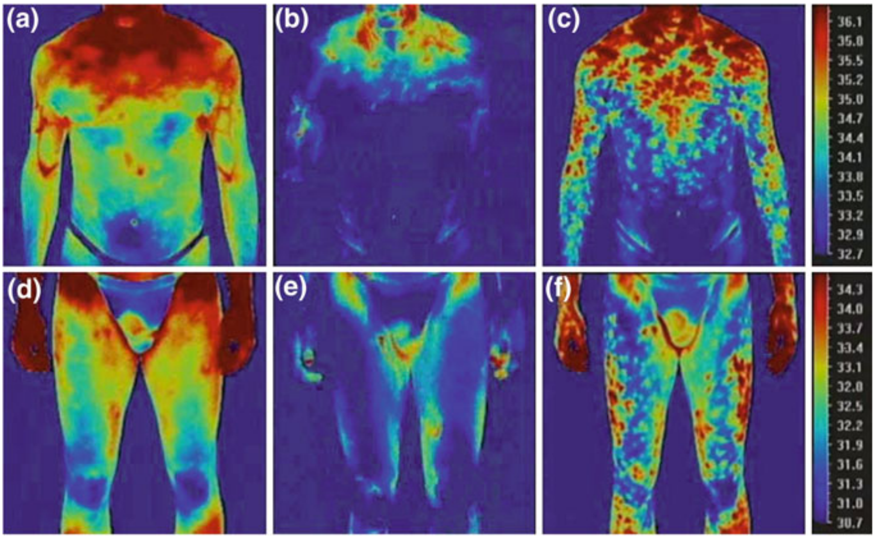

Fig. 5.5 Anterior view of the upper and lower body of a representative participant taken before running (**a**, **d**), immediately after reaching the age-predicted maximal heart rate value during incremental running test (**b**, **e**); and during recovery from exercise (**c**, **f**). Figure obtained from Merla et al. [40]

body. However, the continuous decrease in skin temperature observed during exercise should be attributed not only to the decrease in skin blood flow, but may be also related to a small amount of sweat delivery, even it seems to play a secondary role [30].

All in all, the interpretation of the dynamic process of skin thermal regulation obtained from thermal imaging requires a basic understanding of physiological mechanisms of skin blood flow and factors that influence thermoregulation processes. Researchers have combined the use of infrared thermography with techniques providing more direct measurements of blood flow, to better understand the complexity of thermoregulation processes. For this purpose, a study by Merla et al. [52] proposed a non-invasive method to calculate blood flow by means of thermal infrared imaging and bio-heat transfer modeling. The method, able to provide high time-resolution series of cutaneous blood flow images, was tested against a standard laser Doppler imaging system, which is considered the gold standard for non-invasive assessment of skin blood flow, on both healthy subjects and patients suffering from systemic sclerosis [52]. However, to the best of our knowledge, no studies have combined the measure of skin temperature by infrared thermography with the measure of skin blood flow by laser Doppler during exercise. This should be the further step for advancing the knowledge about the thermoregulatory processes occurring at the skin level during different types of exercise and/or conditions.

5.4 Effect of the Exercise Characteristics on Skin Temperature Response

As it was mentioned in the previous sections of this chapter, skin temperature could present increases or decreases depending on the characteristics of the study and the ROI investigated. In order to understand all the factors that could affect the skin temperature behaviour during exercise, first it is important to check the heat balance equation, i.e., an equation that it is often used in the in mathematical calculation of thermoregulation:

$$\begin{aligned}&\text{Heat production} = \text{Heat loss, and more specifically :}\\&\mathrm{M} - \mathrm{W} = (\mathrm{K} + \mathrm{C} + \mathrm{R} + \mathrm{ESK}) + \mathrm{S}\end{aligned}$$

where M is the rate of metabolic heat production, W is the rate of mechanical work, K is the rate of conductive heat loss, C is the rate of convective heat loss from the skin, R is the rate of radiative heat loss from the skin, ESK is the rate of evaporative heat loss from the skin, and S is the rate of body heat storage.

Higher values on one side of the equation could explain greater increases or reductions in skin temperature. Thus, high increases of skin temperature would be explained by high heat production and low capacity of heat loss, and high reductions by low heat production and high capacity of heat loss. Below there is a summary of what are the factors that affect heat production and heat loss:

- Heat production (metabolic rate—mechanical work): metabolic cost of the exercise, duration and intensity.
- Heat loss: heat dissipation by conduction, convection, radiation, and evaporation, and external work. At the same time, these processes depend mainly on the following factors: environmental conditions (temperature, humidity, wind speed and radiation), clothing, body surface and sweat rate.

After sum up all the factors that can influence skin temperature, it is easy to understand why skin temperature does not always follow the same pattern. Other factors that could affect skin temperature (e.g., circadian rhythm) are explained in the Chap. 3 of this book.

To develop this section, it was decided to conduct a review of the effect of exercise on skin temperature in the different studies, taking into account some of the above factors. The overview of the studies is shown in Table 5.1. In particular, the Table aims to summarize the studies assessing both the magnitude and the direction of skin temperature changes in response to exercise with respect to basal pre-exercise condition. Ten studies were selected using the following criteria in order to present the last and most representative researches: (1) published after 2005, (2) more than 10 participants, (3) ROIs excluding foot and hands for its particular physiology, (4) published in international peer-reviewed journals and written in English, and (5) avoid repetitive characteristics. The last criteria means that if there are some studies with different objectives but with similar experimental conditions, only one study was selected (i.e., the study with the higher number of participants). An example of this criterion are the studies performed by Priego Quesada and colleagues [16, 30, 53, 54] where the objectives are different but in all of them the characteristics of the exercise (45 min of moderate cycling) and environmental conditions are the same.

After review the Table 5.1, it is possible to extract some ideas:

- The environmental temperature ranges from ~20 to ~25 °C, with relative humidity from 45 to 63%.
- Skin temperature response to exercise has been investigated following cycling or running exercises, sports game activities and resistance exercises. In cycling and running exercise, it is worth distinguishing between constant load submaximal exercise [16], and incremental maximal exercise until exhaustion [40, 41].
- The different studies suggested that there are differences in the skin temperature response between the ROIs analysed. As previously was mentioned, skin temperature in specific regions of the body is the result of a thermal balance between muscle activity, vasodilation and sweat evaporation [3, 24, 54].
- The studies that assessed stable load submaximal exercise [28, 54, 55] showed a skin temperature increment of active muscle. Although it is difficult to affirm that skin temperature of active muscles increases in constant exercise, it is

Table 5.1 Overview of some of the most representative IRT studies in sport and exercise physiology

No.	Study	Participants characteristics	Environmental conditions	Exercise characteristics	Result ΔSkin temperature
Stable workload					
1	de Andrade Fernandes et al. [28]	12 males physically active	25 ± 1 °C, 62 ± 6%	Running. 12 blocks of 5 min each at the 60% of the VO_{2max} separated by an interval of 1 min	Mean skin temperature: ~↓0.5 °C Arm: not changes Thigh: ~↑0.5 °C
2	Priego Quesada et al. [55]	29 males runners and 15 females runners	24 ± 1°C, 49 ± 11%	Running, 10 min warm up and 20 min at 75% maximal aerobic speed (aerobic high intensity)	Knee extensors: ~↑1 °C Knee: ~↑2 °C Anterior ankle: ~↑1.5 °C Achilles: ~↑3 °C Rest of lower limb ROIs: not changes
3	Priego Quesada et al. [54]	19 males trained cyclists	24 ± 1 °C, 45 ± 12%	Cycling, 45 min at 50% peak power	Knee extensors: ~↑1 °C Rest of body ROIs (trunk and lower limbs): not changes
Incremental workload					
4	Merla et al. [40]	15 males trained runners	23–24 °C, 50 ± 5%	Running, incremental test until exhaustion	Trunk: ~↓2 °C Forearm: ~↓4 °C Thigh: ~↓5 °C
5	Abate et al. [56]	20 trained runners and 20 sedentary males	23 ± 1 °C, 55 ± 10%	Cycling. Three steps: 5 min at 100 W, 5 min at 130 W and 5 min at 160 W	Trunk: ↓~0.9 °C trained Not changes untrained Upper limbs: ↓~0.8 °C trained Not changes untrained
6	Arfaoui et al. [57]	11 male cyclists	20 ± 1 °C	Cycling, incremental test during 18 min until 250 W	Gastrocnemius: ↓~1 °C
7	Priego Quesada et al. [41]	10 males physically active	20 ± 1 °C, 63 ± 3%	Cycling, incremental test until exhaustion	Knee extensors: ~↑1.5 °C Biceps femoris/gastrocnemius medialis: not changes

(continued)

Table 5.1 (continued)

No.	Study	Participants characteristics	Environmental conditions	Exercise characteristics	Result ΔSkin temperature
Training game session					
8	Chudecka and Lubkowska [23]	16 professional males handball players	20 °C training and 25 °C thermography room, 55%	Training session 90 min: endurance training and handball game	Upper extremities: ~↓2.4 °C
Resistance exercise					
9	Ferreira et al. [37]	14 elderly and 15 young	22–24 °C, <50%	Resistance exercise. One limb 3 min knee extension and flexion with a 1 kg weight.	Posterior thigh exercised limb: not changes Posterior thigh contralateral rest limb: ~↓0.5 °C
10	Formenti et al. [38]	7 trained and 7 untrained females	22–23 °C, 60 ± 5%	Resistance exercise with body weight, 2 min standing calf raise.	Calves: ~↑1.0 °C trained ~↑0.4 °C untrained

possible to suggest that in this kind of exercise the heat production of this area is higher than no active muscles, showing larger increases or lower decreases of skin temperature during exercise.

- There are discrepancies in skin temperature response between the different studies. For example, in the study by Merla and colleagues [30], an incremental maximal exercise [40] induced a large decrease in skin temperature of active muscles during running, whereas incremental maximal cycling exercise tested by Priego Quesada et al. [41] induced an increase. Differences between the two exercises could be related with the kind of exercise (running vs. cycling). However, it is important to remind that other factors could affected these differences: duration of the exercise, environmental differences (i.e. differences in relative humidity), differences between participants in fitness level, age, body composition, etc.
- Resistance exercise with body weight studied by Formenti et al. [38] induced an increase in skin temperature of the calf area. Conversely, resistance exercise with very low load (i.e., 1 kg) studied by Ferreira et al. [37] did not produce any modifications on active muscles. Resistance exercises may have a lower sweat production (in some cases non-existent). This could result in a direct association between intensity of exercise and skin temperature response, contrary to what happens to other exercises (e.g., cycling and running) that result in a whole body sweating. However, further studies are necessary to research this idea.

All in all, there is a large heterogeneity in the methodology used, that depends also on the purpose of the study. Differences can be found in the sample characteristics, exercise characteristics, as well as region of interests considered. Due to this heterogeneity, it is generally difficult to find a common point among the studies.

5.5 Relationship Between Skin Temperature and Performance Variables

Most of the studies that have investigated the skin temperature modifications associated to exercise by IRT have focused on identifying possible relationships between skin temperature values and performance parameters. Among them, the performance variables most studied are undoubtedly cardiorespiratory parameters, such as maximal oxygen uptake (VO_{2max}) and heart rate.

The relationship of skin temperature changes with cardiorespiratory parameters associated to exercise have been studied both during team sport training [23], endurance cycling exercise [57], and resistance exercise [58]. Chudecka and Lubkowska [23] published a study aimed to investigate the temperature changes in arms and forearms in response to a 90 min physical exercise session. Furthermore, the authors investigated also the impact of physiological factors (such as VO_{2max} and heart rate) on the dynamics of temperature changes. Sixteen professional handball players performed a training session lasting 90 min, which contained elements of the actual game, such as sport specific plays. The session was performed in a sports hall with air temperature of 20 °C and air humidity of 55%, i.e., thermal neutral environment. The skin temperatures of arms and forearms were registered before, immediately after and 10 min after the training session. They obtained a regression model with a significant correlation when the participants with a higher fitness level (by VO_{2max}), higher percentage of the maximum heart rate during the training season, and lower skin-fat fold on the arm, presented a higher decrease in skin temperatures after exercise. The reduction in the skin temperature after the training session was primarily attributed to the efficacy of sweat evaporation mechanism. The authors concluded stressing that players with higher fitness level (VO_{2max} and lower fat body composition) may be beneficial by better thermoregulatory response. Furthermore, a possible explanation regarding the higher decrease in skin temperature in players with a higher percentage of the maximum heart rate was that these players exercised with greater intensity, thus probably sweating more. This in turn implicates a more efficient heat elimination, and of consequence larger decrease in skin temperature after the end of the training session [23].

If Chudecka and Lubkowska [23] investigated the relationship between performance variables and skin temperature after an handball training session, another research group published two studies investigating such relationship in cycling exercise [57, 59]. In the more recent study, Arfaoui et al. [57] investigated the relationship of skin temperature of gastrocnemius with heart rate during an incremental cycling exercise. Eleven subjects performed an incremental cycling exercise on a cycle ergometer. The exercise began at a power output of 100 W (10 min), and then the intensity increased in increments of 50 W every 3 min, each up to 200 W, whereas the last load was performed at 250 W for 2 min. Skin temperature (measured by infrared thermography) and heart rate were recorded continuously during the experiment. Skin temperature values at each stage of the exercise were reported as variations with respect to basal values. Dynamics of skin temperature and heart rate during exercise are reported in Fig. 5.6. Immediately at the onset of the exercise, skin temperature of the calves drastically decreased. This rapid fall in skin temperature during initial stage of the exercise was not attributed to increased evaporative cooling but to vasoconstriction related to the muscular blood recruitment [6]. This phase was followed by a steady state period, thus meaning the presence of a thermal equilibrium between heat production and heat dissipation reflected on the skin. Prolonging exercise increased the metabolic heat production thus invoking thermoregulatory processes. In fact, an important decrease in the skin temperature occurred as exercise intensity increased (i.e., from 150 W at each load). Heart rate showed a quasi-perfect reverse dynamic with respect to skin temperature, thus proving the presence of a strong relationship between the two variables. This was also confirmed by the significant correlations found by the authors between heart rate and the skin temperature variations during the phase of 100 W ($r = 0.9$), and the incremental phase until 250 W ($r = 0.99$).

The relationship between skin temperature and heart rate was also investigated and assessed during resistance exercise. Neves et al. [58] studied the association between the skin temperature change and the heart rate response during two

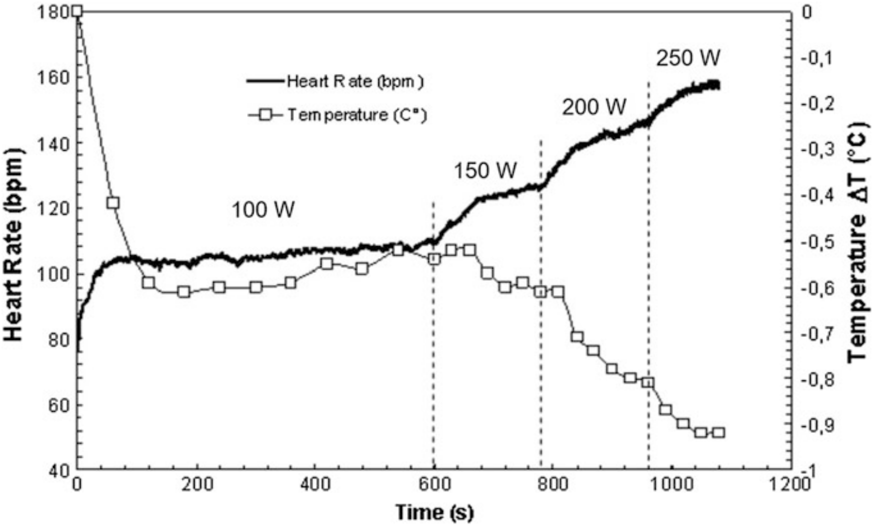

Fig. 5.6 Heart rate and skin average temperature gradient during incremental cycling test. Figure modified from Arfaoui et al. [57]

sessions of resistance exercises at different intensities. A sample of 31 female subjects were divided in two groups: 15 subjects performing unilateral biceps curl, and 16 subjects back half squat at 90°. The exercise protocol of both biceps curl and squat was repeated in two randomized sessions (70% of 10 RM and 80% of 10 RM). The exercise protocol consisted in four sets with 10 repetitions in each set, and with 30 s to rest between them. The heart rate and skin temperature in the two groups were recorded continuously before, during and after exercise. Skin temperature on the active muscles decreased during exercise and during the first minutes of the recovery period, returning to basal values within one hour of recovery after exercise. There were no statistical differences in thermal response to exercises in 70 and 85% of 10 RM in both biceps curl and squat group. Significant negative correlations between heart rate and skin temperature during exercise were found in the 70% of 10 RM session only in the squat group, whereas in the 85% of 10 RM session both in the biceps curl and squat group. Moreover, significant negative correlations were also found in the recovery in the 70 and 85% of 10 RM, both in the biceps curl and squat group. The authors concluded stressing that skin temperature on the active muscles decreased during exercise and during the first minutes of the recovery, returning to basal values slowly.

Infrared thermography have been also used to assess the difference in thermoregulation between subjects with different level of physical fitness [38, 56, 60]. Based on the fact that higher fitness level is associated with higher skin blood flow during exercise [61], Merla et al. [60] conducted an experiment aimed to compare the skin temperature response to an incremental cycling exercise between trained and untrained subjects. After an initial trend that was similar in both groups, trained subjects exhibited a higher decreasing temperature rate with respect to the untrained ones. These findings seems to support the hypothesis that the muscular capability to recruit blood to supply its needs during an exercise is better in trained subjects than in untrained ones [60].

Further evidences in this direction have been more recently provided by the studies by Abate et al. [56] and by Formenti et al. [38]. In these studies, the authors investigated the influence of physical fitness on exercise-associated skin temperature changes. It was hypothesizing that exercise can induce differences in the trends of skin temperature between trained and untrained subjects. As regards to the study by Formenti and colleagues [38], 7 trained and 7 untrained female subjects performed standing calf rise exercise lasting 2 min, with a constant pace consisting in 1 s eccentric and 1 s concentric phase, with the aim of a metronome. Skin temperature of the calves were measured before, during, and for 7 min after the exercise. By comparing the parameters describing the skin temperature time course in two groups, it was found that trained subjects, after a slightly decrease due to vasoconstriction recruiting blood flow to the active muscles, increased their skin temperature differently with respect to untrained subjects. Specifically, trained subjects responded to exercise more quickly than untrained controls.

Also the study by Abate et al. [56] supports the findings by Formenti et al. [38]. In this study [56], the authors investigated the differences in the cutaneous temperature among trained and untrained subjects. 20 trained and 20 untrained male subjects performed a standard cycling warm up, divided in three steps: (1) 0–5 min at 100 W; (2) 5–10 min at 130 W; and (3) 10–15 min at 160 W. Thermal images of thorax and upper limbs were recorded during the exercise. With respect to baseline, trained subjects exhibited a significant temperature decrement in the third step in both trunk and upper limbs, while no difference was observed in untrained subjects. In the comparison between groups, a statistically significant difference was observed in both regions of interest (i.e., trunk and upper limbs), in the second and in the third step. In conclusion, the findings of these study support the notion that the level of physical fitness improves the ability to rapidly activate thermoregulatory processes in response to exercise [38, 56].

Since surface electromyography permits to estimate the magnitude of electrical neuromuscular activity during exercise, it was also hypothesized the existence of a relationship between muscle activation during exercise and associated-skin temperature modifications [41, 62]. The study by Bartuzi was probably the first assessing this relationship [62]. It was observed an inverse relationship between biceps brachii activation and skin temperature during fatigue isometric contractions. Based on these findings on isometric exercise, another group of research investigated the relationship between neuromuscular activation (measured using surface electromyography) and skin temperature of different body area (measured using infrared thermography) during an incremental exercise on a cycle ergometer [41]. Subjects performed an incremental cycling test until exhaustion on a cycle ergometer. The incremental cycling test started with initial workload of 50 W lasting 3 min, and it was followed by increments of 25 W/min until reaching the complete exhaustion. Pedaling cadence was controlled at 90 ± 3 rpm. Peak power output was identified as the workload of the last stage. Skin temperature of front and back surface of subjects' thighs was recorded in three different times during the experiment. Neuromuscular activation was monitored using surface EMG from the right and left rectus femoris, vastus lateralis, biceps femoris and gastrocnemius medialis throughout the duration of the test. No significant correlations between skin temperature and neuromuscular activation were found in rectus femoris, biceps femoris and gastrocnemius medialis. In fact, the relationship observed was in vastus lateralis, and it was more related with fitness level and not with the heat generated by the muscle. Participants with higher overall neuromuscular activation and lower frequency content in activation for vastus lateralis presented lower increments of skin temperature, or what is the same, better thermoregulatory response. This profile of neuromuscular activations was associated with better fitness level.

Finally, it is important to remark the association between fat composition and skin temperature. Priego Quesada et al. [41] observed that participants with larger thigh skinfolds presented lower increments of skin temperature in ROIs of the thigh ($p < 0.01$ and $r > -0.7$). These authors discussed two points about this association. Firstly, it is clear that body fat tissue had an insulation capacity resulting in impairment of the heat dissipation between the core and the skin [23, 63, 64]. Moreover, it is worth considering that fat tissue is related to the physical fitness [65]. Body composition is one of the factors that change with the training and this variable can be one of the factors that explain the differences between people with different fitness capacity. On the other hand, Chudecka and Lubkowska [23] selected this ROI in their study in relation with the fat tissue composition. They suggested that upper limbs are appropriate ROIs to analyze the effect of a training session for its lower adipose tissue and then less effective thermal insulation.

5.6 Conclusion

In this chapter we presented a general overview on the literature about the study of the skin temperature response to exercise assessed by means of IRT and its relationship with other thermoregulatory variables, exercise characteristics and performance factors. Some conclusions could be extracted from the chapter:

- IRT presents some differences in the skin temperature calculation in comparison with the thermal contact sensors, and also some advantages and limitations. Generally, IRT presents lower values of skin temperature during exercise than thermal contact sensors. Furthermore, IRT could provide the measurement of large areas without interfere in the heat exchange of the subject. However, it is not possible to measure when the subjects are clothed and the sweat could interfere in the temperature calculation. This advantages and limitations are important to take into account before and after a study.

- The experimental approach (e.g., measure during exercise or before-after exercise) and the characteristics of the exercise will influence the skin temperature, and researchers should be aware in the design of the experiment.
- Skin temperature is the result of different thermoregulatory variables such as blood flow, sweat rate and core temperature. It is important to know the role of all these variables in order to interpret correctly the skin temperature changes.
- Differences in skin temperature response to exercise between studies in the literature are due to heterogeneity in exercise characteristics, as well as region of interests considered.
- People with better physical fitness presents a more effective thermoregulatory system or, what is the same, a greater capacity of heat dissipation. Because of this, different studies have observed relationships between some performance parameters and skin temperature.

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Chapter 6
Infrared Thermography in Water Sports

Ricardo Vardasca, Adérito Seixas, Joaquim Gabriel
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Abstract Likewise any other sport, water sports can also be objectively assessed through a physiological method such as thermal imaging. This particular type of sports present an extra parameter, which is the particular environment were it happens. In this chapter it is outlined the underlining concepts, challenges and methods, along with the related published research to date in the field with practical examples and future lines of research are proposed.

6.1 Introduction

Exercise training causes adaptations in the skin blood flow response to exercise, including changes in cutaneous microvascular reactivity. Increases in skin blood flow at a given exercise core temperature appear to be related with the expansion of blood volume and increased cardiac output that characterize the trained state. In contrast, adaptations in the cutaneous microvasculature are mediated by changes in

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the biological availability or activity of endothelium-derived vasoactive compounds [1]. Changes in skin temperature are known to be affected by blood flow [2], and skin temperature are passive of being passively captured and posteriorly analyzed through thermal imaging, a non-contact, non-invasive and non-ionizing imaging technique that registers the surface emitted thermal radiation into radiometric temperature maps [3].

Water sports, being swimming one of the major examples, induce changes in blood flow through the exercise, where heat is produced by the muscles, and the contact with water highly influences the skin thermoregulation. These two aspects can be object of monitoring using thermal imaging investigating skin temperature changes.

One of the basic functions of the human body is to keep core body temperature constant between 36 and 37.5 °C, keeping its vital functioning. This is maintained by the hypothalamus, which receives constant information from the autonomous nervous system, taking advantage in the different body thermal sensors, placed close to the vital organs internally and at the periphery at the skin dermis. The skin is the major organ of the human body and plays a major role in the interface with the surrounding environment. The neutral zone for the skin thermal body sensors is within an ambient temperature between 18 and 24 °C at a relative humidity of less than 50%. Below this value the temperature recovery mechanisms such as vasoconstriction, muscle shivering and increasing of the metabolic rate are activated. On the other hand above 24 °C the temperature release mechanisms are activated, consisting in vasodilatation and sweating [4, 5].

Water sports and in particular swimming, as any other sport, challenges the thermal balance of the human body, increasing the skin temperature [6] through a complex thermoregulation process that intends to preserve core temperature around 37.5 °C [7]. Despite the study of Wade and Veghte [8] and the increasing number of papers in sport research reporting the use of thermal imaging, its use in swimming research is limited and few researchers have informed the use of this technology in swimming activities [6, 9, 10].

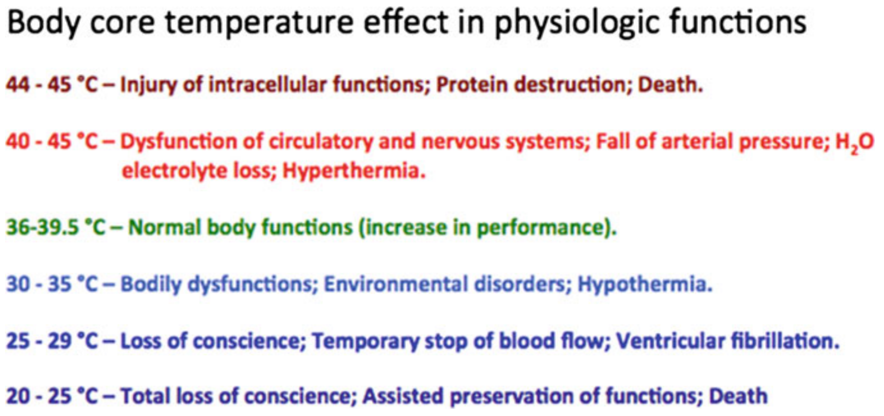
6.2 Relationship Between Skin Temperature, Exercise and Water Exposure

Water is one of the most simple examples of matter that can easily change its state with the internal molecules activity. It is known that at temperature below 0 °C it solidifies, become solid, and at temperatures above 100 °C it boils, becoming a gas. Within this intervals the water stay in its liquid state, when in contact with it the human body starts to exchange thermal energy through forced convection. The physical properties of the water change according to its state, at a liquid state its emissivity value is of 0.97 [11], very close to the human skin value (0.98). However the presence of water in the skin causes an undesirable effect of blocking the spontaneous skin ability of radiating thermal energy. It worth also to mention that water is a much better heat conductor than air, about 25 times more effective [5]. The first major challenge of this type of research is to measure the thermal effect of any exercise, minimizing the water associated issues related to thermoregulation. Good understanding of how the water conditions and exposure can affect thermoregulation and the effect on human body core temperature is required to prevent undesired loss of physiological functions as presented in Fig. 6.1 [12].

In water temperatures of 25 °C and below, oxygen consumption (VO_2) increases at a faster rate than air at temperatures of 25 °C, and cardiac frequency is reduced [13, 14]. Oxygen consumption increases because the muscle tremor generates thermogenesis and possibly a decrease in mechanical ability during exercise. The cardiac output increases linearly with an increase in peripheral vasoconstriction in cold water. When water temperatures are at 30 °C and above, metabolic rate and cardiac frequency are the same in both air and water environments.

If the increase of pulses volume is due to the effects of hydrostatic pressure from the increasing peripheral vasoconstriction, then cardiac frequency could be depressed in warm water. Heat dissipates faster in cold water, and swimming in sub-maximal temperatures reduces the human body's core temperature, even if the metabolic rate increases [15]. The increase in metabolic rate is inversely proportionate to the increase in water temperature. The levels of lactic acid are increased during submaximal swimming distances in cold water, while muscle temperatures could alter physical and chemical functions in the muscle's interior during swimming, ultimately resulting in the reduction of mechanical ability in cold water [12].

Immersion of the skin in water results in a characteristic whitening and wrinkled appearance associated with the uptake of significant quantities of water. The rate of evaporation from hydrated skin surfaces is considerably in excess of that from



Body core temperature effect in physiologic functions

44 - 45 °C – Injury of intracellular functions; Protein destruction; Death.

40 - 45 °C – Dysfunction of circulatory and nervous systems; Fall of arterial pressure; H_2O electrolyte loss; Hyperthermia.

36-39.5 °C – Normal body functions (increase in performance).

30 - 35 °C – Bodily dysfunctions; Environmental disorders; Hypothermia.

25 - 29 °C – Loss of conscience; Temporary stop of blood flow; Ventricular fibrillation.

20 - 25 °C – Total loss of conscience; Assisted preservation of functions; Death

Fig. 6.1 Effect that body core temperature has in the physiological functions, describing its undesired risks non-hydrated areas. Although, prolonged immersion suppresses sweating on the palm of the hands and feet sole [16], not being these areas recommended for skin temperature assessment with thermal imaging.

After stabilization of body temperature at rest in the coldest possible water (12 °C), exercise reduced internal insulation only in muscular parts of the limbs. Exercise also increased heat loss elsewhere by exposing skin of protected regions such as flexural surfaces of joints. During exercise total heat production increased rather more than heat loss in unreactive subjects, but less than loss in subjects whose heat production had already risen to a high level when they were at rest in cold water [17].

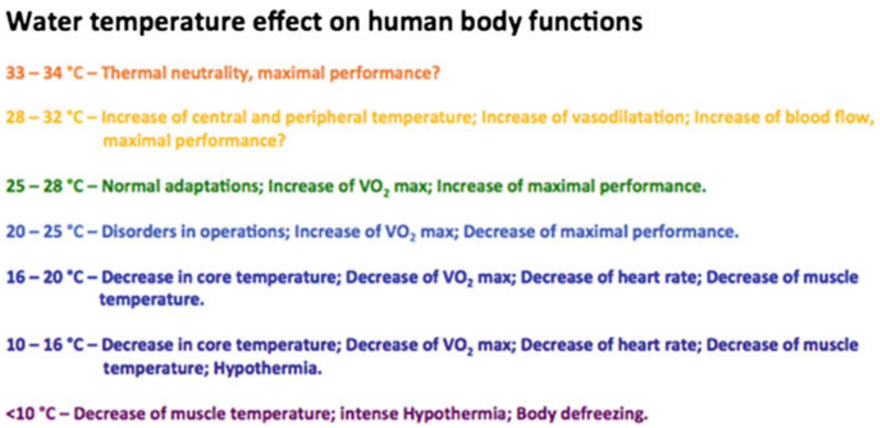
In warm water (37 °C), tissue insulations were lower and much more uniform between subjects and between different body regions than in the cold. Even in the warm, however, insulations remained rather higher in fat than thin subjects, higher at rest than during exercise, and usually higher in the limbs than the upper trunk [17].

Repeated cold water immersion produces acclimation to cold air in humans and the cold acclimation is primarily of the insulative type in that skin temperatures are lower, probably due to greater sympathetic nervous system activation mediating stronger cutaneous vasoconstriction. The degree of cold acclimatization achieved is probably related to the intensity (frequency and duration of reduction in core temperature) of the acclimatization procedures employed [18].

Water and electrolyte balances are critical for a person's ability to thermoregulate and perform exercise in the heat. During exercise in the heat, water and electrolyte losses primarily occur from sweating. A person's sweating rate is dependent upon the climatic conditions, clothing worn and exercise intensity. Daily fluid requirements range (for sedentary to very active persons) from 2 to 4 l day in a cool climate up to 8–16 l/day in very hot climates. Over a 24 h period, fluid and electrolyte losses will be replaced if persons consume their normal diet. During exercise, sweat output often exceeds water intake, producing a water deficit or hypohydration. The water deficit lowers both intracellular and extracellular fluid volumes [19].

It also results in plasma hypertonicity and plasma hypovolemia, both of which adversely affect heat loss responses. Aerobic exercise tasks are likely to be adversely affected by hypohydration, with the potential effect being greater in warm environments. Hypohydration increases heat storage by reducing sweating rate and skin blood flow responses for a given core temperature. Hyperhydration provides no advantages over euhydration regarding thermoregulation and exercise performance in the heat [19].

A cold beverage taken in ecological conditions (i.e., small volumes taken regularly during training sessions) had a significant effect on body core temperature, thermal sensation, and heart rate during both training and high-intensity training in high-level swimmers in a tropical climate. The effects were optimal in the evening, certainly in relation with a more stressful environment and/or sensation. Because the aim of using cold water is to decrease the impact of stress to improve performance, studies exploring the effect of cold-water ingestion on performance



Water temperature effect on human body functions

33 – 34 °C – Thermal neutrality, maximal performance?

28 – 32 °C – Increase of central and peripheral temperature; Increase of vasodilatation; Increase of blood flow, maximal performance?

25 – 28 °C – Normal adaptations; Increase of VO_2 max; Increase of maximal performance.

20 – 25 °C – Disorders in operations; Increase of VO_2 max; Decrease of maximal performance.

16 – 20 °C – Decrease in core temperature; Decrease of VO_2 max; Decrease of heart rate; Decrease of muscle temperature.

10 – 16 °C – Decrease in core temperature; Decrease of VO_2 max; Decrease of heart rate; Decrease of muscle temperature; Hypothermia.

<10 °C – Decrease of muscle temperature; intense Hypothermia; Body defreezing.

Fig. 6.2 Effect of water temperature in human body functions

during real competitive events are needed, in both acclimated and unacclimatized high-level subjects [20].

The Fig. 6.2 shows the effects that water temperature has in the human body functions [12].

Water temperature immediately affects bodily functions upon entry into the water, throughout immersion and during swimming, gradually provoking changes, which affect the condition of the organism, as well as its overall performance. The increase or decrease of the water temperature beyond the normal range may act therapeutically, entertainly, or to enhance the body’s physical fitness, but it does not contribute to the improvement of performance [12].

When the human body is immersed in water, body temperature changes. This change due to and influenced by several factors, such as: water temperature, air temperature, air currents, environmental moisture, the composition and percentage rate of tissues in the body, the percentage rate of fat tissue, and the percentage of immersion of the body in water. During exercise in water temperatures between 26 and 28 °C, in healthy adult individuals, a low and pleasant body temperature is observed. This temperature is present in most swimming pools and they have a strong effect on the human body, such as: only a few minutes after immersion of the body in water, skin temperature is equalized with water temperature (with a difference of approximately 1 °C), since heat conductivity is 25 times greater in water than in air [12].

In a state of rest-immobility, in water temperatures of 33–34 °C, the human body acquires thermal neutrality; this allows for mild swimming activities, with entertaining and therapeutic properties. These high temperatures are appropriate for mild activities for infants and children, the elderly, and fragile or injured individuals [12].

At water temperatures below 30 °C, hypothermia progressively sets in. In competitive swimming, any increase or decrease of the water temperatures beyond the normal [21], chain reactions and effects between organs, systems, mechanisms and substances are observed, on the surface and inside the body; these result in changes in their functions and/or activities, and strongly affect the outcome of the swimming effort [12].

The Table 6.1 presents the survival times of an average human subject immersed in cold water without protective clothing, characterizing the loss of dexterity, time of exhaustion or unconsciousness and expected time of survival [22].

When the water temperature is in the range from 28 to 32 °C, there is a tendency for performance to improve, primarily in speed events. However, at temperatures higher than that, performance decreases and other goals are pursued. In temperatures much higher than this range, staying in the water becomes impossible and pronounced phenomena of hypothermia occur [12].

At water temperatures ranging from 25 to 27 °C, there is a tendency for performance to improve, primarily in endurance events. However, at lower temperatures performance drops, and perhaps there is a need to investigate the appropriate temperature for marathon and hyper-marathon swimming [12].

Within the interval between 25 and 20 °C in water temperature, malfunctions appear in the organism, the swimming effort and performance is reduced and remaining in the water becomes difficult, with phenomena of hypothermia [12].

If the water temperature ranges between 20 and 12 °C, pronounced malfunctions appear in the organism, the swimming effort and performance is reduced and remaining in the water becomes difficult, with gradual phenomena of hypothermia. Only practiced, fit individuals can swim in these conditions [12].

When water temperatures drop below 12 °C, pronounced and immediate malfunctions appear in the organism, there is complete inability to swim or perform, inability to remain in the water for longer than 1 h, and pronounced phenomena of hypothermia and cooling of the body [12].

Table 6.1 The survival times of an average human subject immersed in cold water without protective clothing

Water temperature (°C)	Loss of dexterity with no protective clothing	Exhaustion or unconsciousness	Expected time of survival
>26.5	2–12 h	Indefinite	Indefinite
21–26.5	1–2 h	2–12 h	3 h to indefinite
15.5–21	30–40 min	2–7 h	2–40 h
10–15.5	10–15 min	1–2 h	1–6 h
4.5–10	Under 5 min	30–60 min	1–3 h
0.3–4.5	Under 3 min	15–30 min	30–90 min
<0.3	Under 2 min	Under 15 min	Under 15–45 min

6.3 Assessment of Skin Temperature in Water Sports

Acclimatization is important to achieve a pre-imaging thermal equilibrium between the body skin and surrounding environment [23] but the time required is not yet consensual and previous published research recommend time periods of 10 min [24], 15 min [25] and 20 min [26]. These authors suggest that acclimatization should be undertaken at rest in an examination room with controlled thermal environment to obtain baseline thermograms when using dynamic thermal imaging. In particular, swimming exercise is performed in the water and if baseline thermograms would be obtained in such conditions the analysis would be wrong and meaningless.

Water is an isotropic substance and opaque to skin radiation [27]. Therefore swimmers must be dried before thermal imaging acquisition. In this process skin friction must be avoided since it can influence local microcirculation and cause unwanted increase in the skin temperature values measured with the thermal images.

This issues where researched by Zaidi et al. [6], however their work was limited, further research is recommended.

The first known application of thermal imaging in water sports was performed by Wade and Veghte [8] on investigating the regional differences in skin temperature in 4 competitive swimmers of varying body compositions, prior to and after 5 min of immersion in water at 23.5 °C, and after a 500-m freestyle swim at a training pace. Decreases in skin temperature that correlated with skinfold thickness were seen post-immersion. After swimming, skin temperatures were highest in regions overlying active muscle masses (deltoids, trapezius, triceps and biceps brachi, and pectorals) and were independent of skinfold thickness. It was also found that thin swimmers were found to dissipate faster the heat than fat subjects.

Another study a few years later attempted to determine the thermal and metabolic effects of wearing a rubberized wet suit when compared with a competitive swimming suit while swimming for 30 min in 20.1, 22.7, and 25.6 °C water, with a 15 min resting period between them. Nine subjects were investigated and skin temperature was obtained not with thermal imaging but with skin temperature sensors (TX-4 Columbus instruments). The rubberized wet suit present a significant higher body temperature than the competitive swimming suit, that difference decreased when the water temperature become warmer [28].

Hue et al. demonstrated that training in a tropical climate significantly enhances performance in swimmers (400 m freestyle), 30 days after return to neutral climate [29]. A sample of 16 swimmers was used and the climates compared were the tropical and the neutral, there were 3 moments used, the baseline, 10 days after and 30 days after. No relation was obtained between the 10 and 30 days post training.

A preliminary experimental study was undertaken for studying the feasibility of using thermal imaging in the discipline of swimming and for quantifying the influence of the swimming technique (within the framework of a well defined protocol) on the distributions of skin temperatures [6]. They have used an uncooled

FLIR ThermaCAM FLIR SC1000 (sensor array size of 256 × 256, NETD of <70 mK at 30 °C and measurement repeatability of ±2% of the overall reading) and a cooled CEDIP TITANIUM HD 560 M (sensor array size of 640 × 256, NETD of <40 mK at 30 °C and measurement repeatability of ±2% of the overall reading) thermal cameras. Significant variations were found in the cutaneous temperature according to the swimming styles. From the examination of infrared thermography, the whole body surface, has respectively increased by 2.16 °C for the butterfly, 2.56 °C for the backstroke, 1.78 °C for the breaststroke and 2.00 °C for the freestyle, after the single participant had performed the 400 m test in each technique on different days. The swimmer had spent 10 min of acclimatization period in the pool with water at 27 °C. The thermal images were taken from swimmer after the period of acclimatization and after 100 m of each swimming technique (butterfly, backstroke, breaststroke and free style). Between each swimming technique performance there was a 10-min rest period to achieve thermal balance and the thermal imaging measurements were performed after this period were the baseline for the swimming technique performed after. The authors presented changes in skin temperature after each swimming technique and concluded that each technique changed the skin temperature differently. Although this study presented a new methodology to assess skin temperature after swimming exercise, some questions are still open, only one swimmer was assessed and the fact that all swimming techniques were performed in the same day since, with a 10-min resting period to achieve thermal balance between different exercises, is it enough? Does fatigue played any role in the observed temperature changes? Nothing was mentioned describing the velocity and intensity of each swimming technique, which may bias the presented results.

Another study compared the physical activities of swimming and practicing yoga in pregnant women [30]. It was found that swimming reduced the skin temperature in the breast and belly regions whereas yoga as presented an increase in most of the skin temperature areas, this may be due to the cooling effect of water. A FLIR T335 (sensor array size of 320 × 240, NETD of <50 mK at 30 °C and measurement repeatability of ±2% of the overall reading) uncooled thermal camera was used, the participants had engaged in a 10 min acclimatization period in a controlled environment room, the images after practice were taken 10 min after the exercise at the same conditions and in the swimming group after the participants dried the skin with towels without rubbing [30]. The acclimatization period and the drying method and subsequent 10 min waiting period may have bias the obtained results.

Five of twenty muscle regions have notable tendencies of increased temperatures, including a front part of deltoideus at right side which is very active by spreading arm forward and beginning of swimming stroke. In nine areas of main agonist swimmers movement forward included—triceps brachii, it was found no significant lowering temperatures. That can be due to the cooling effect of the swimmer in the water. A Fluke TiR (sensor array size of 160 × 120, NETD of <90 mK at 30 °C and measurement repeatability of ±2% of the overall reading) uncooled thermal camera was used. The water temperature was at 27 °C, it was no acclimatization in the water and the post exercise images were taken 15 min after coming out of the swimming pool and being dried with a towel avoid rubbing [31]. The use of an acclimatization period with different conditions from the exercise and a non-recommend low specifications thermal camera for human skin screening [32, 33] may have biased the obtained results.

A study investigated the possible relationship between energy expenditure and skin temperature during 2 × 300 m protocols (front crawl and backstroke), performed at the same intensity and velocity, by 2 male experimented swimmers [9]. Both swimming techniques increased skin temperature but with different thermal patterns. Higher values of energy expenditure during the 300 m backstroke test were found comparing with the values obtained for the same distance performed in front crawl and higher difference between skin temperatures values were associated with lower energy expenditure values. The swimmers have refrained an acclimatization period of 10 min immersed still in water at the pool till the head at a temperature of 27 °C. A FLIR A325sc (sensor array size of 320 × 240, NETD of <70 mK at 30 °C and measurement repeatability of ±2% of the overall reading) uncooled thermal camera was used.

A research conducted in Czech Republic has found that there is a significant increase (normalized units) 15 min after swimming in triceps brachii (on the right prior to swimming 0.950 and after swimming 0.994; on the left prior to swimming 0.947 and after 0.990), and in side, rear and front parts of the deltoid muscles [34]. On the contrary, there was a significant relative decrease in temperature in pectoralis, rhombic and lower trapezius, erector spinae lumbalis and latissimus dorsi. It can be concluded that swimming 1000 m breaststroke affected significant increase in the temperature of regions of interest, i.e., corresponding to agonists and synergists of upper extremities for the swimmer's forward motion. A relative decrease in temperature occurred rather in body muscles. The problem of biased results due to water-cooling was solved by using thermograms taken only in the 15th minute after getting out of water and calculating relative temperatures with normalized units. A Fluke TiR (sensor array size of 160 × 120, NETD of <90 mK at 30 °C and measurement repeatability of ±2% of the overall reading) uncooled thermal camera was used, which does not meet the minimum specifications for human skin screening [32, 33].

A study attempted to develop a methodology to investigate swimmers and verify whether there is a considerable change in skin temperature during different swimming techniques (7 × 200m protocol in front crawl and backstroke) and, if confirmed, to identify the most affected regions [10]. A FLIR A325sc (sensor array size of 320 × 240, NETD of <70 mK at 30 °C and measurement repeatability of ±2% of the overall reading) uncooled thermal camera was used. A total of 10 experienced swimmers had been investigated in two consecutive days at same time, performing in the first day the crawl technique and on the second day the backstroke technique.

The regions used were: For anterior view (Fig. 6.3), Anterior Neck Right; Anterior Neck Left; Anterior Torax Right; Anterior Torax Left; Anterior Arm Right; Anterior Arm Left; Anterior Forearm Right; Anterior Forearm Left; Anterior

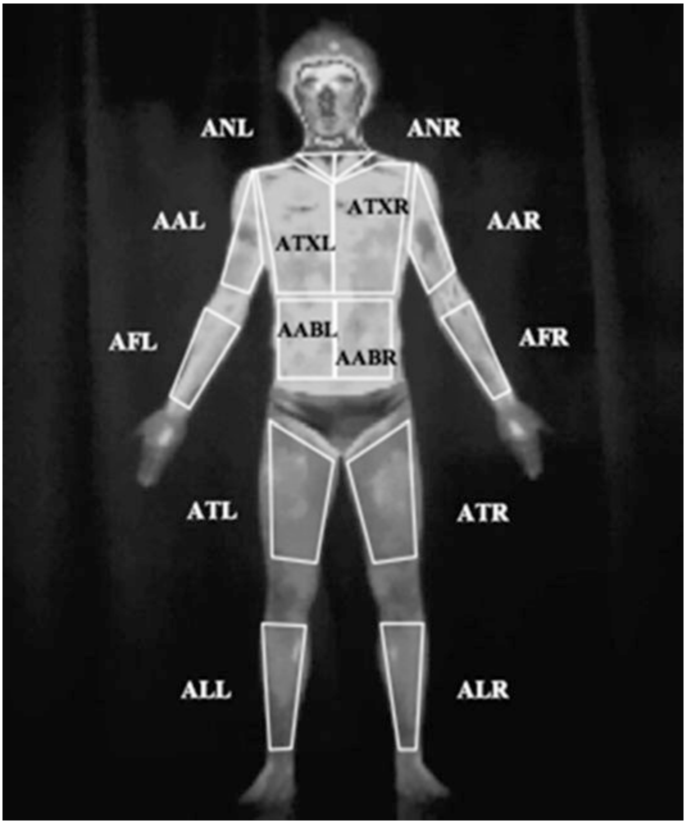


Fig. 6.3 Anterior regions of interest used in the study: Anterior Neck Right (ANR); Anterior Neck Left (ANL); Anterior Torax Right (ATXR); Anterior Torax Left (ATXL); Anterior Arm Right (AAR); Anterior Arm Left (AAL); Anterior Forearm Right (AFR); Anterior Forearm Left (AFL); Anterior Abdomen Right (AABR); Anterior Abdomen Left (AABL); Anterior Thigh Right (ATR); Anterior Thigh Left (ATL); Anterior Leg Right (ALR); Anterior Leg Left (ALL)

Abdomen Right; Anterior Abdomen Left; Anterior Thigh Right; Anterior Thigh Left; Anterior Leg Right; and Anterior Leg Left. For dorsal view (Fig. 6.4), Dorsal Neck Left; Dorsal Neck Right; Dorsal Upper Back Left; Dorsal Upper Back Right; Dorsal Arm Left; Dorsal Arm Right; Dorsal Middle Back Left; Dorsal Middle Back Right; Dorsal Forearm Left; Dorsal Forearm Right; Dorsal Lower Back Left; Dorsal Lower Back Right; Dorsal Thigh Left; Dorsal Thigh Right; Dorsal Leg Left; and Dorsal Leg Right (DLR).

There were collected half-body view images and full-body view images, being the fist collected at a distance of 2 m and the second at 4 m. In both type of views the ROIs were analyzed in terms of mean temperature and between bilateral ROIs, the thermal symmetry [35] was analyzed.

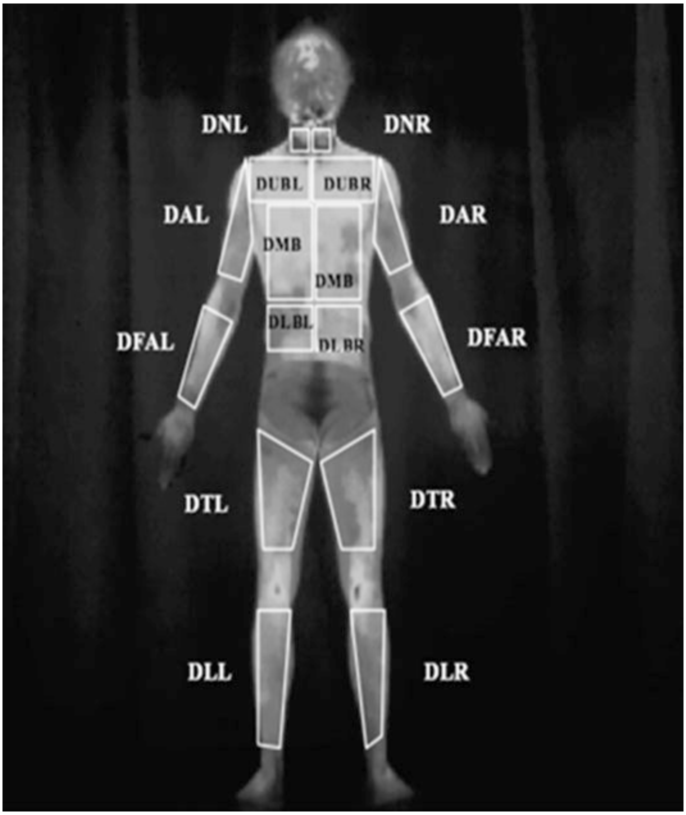


Fig. 6.4 Dorsal regions of interest used in the study: Dorsal Neck Left (DNL); Dorsal Neck Right (DNR); Dorsal Upper Back Left (DUBL); Dorsal Upper Back Right (DUBR); Dorsal Arm Left (DAL); Dorsal Arm Right (DAR); Dorsal Middle Back Left (DMBL); Dorsal Middle Back Right (DMBR); Dorsal Forearm Left (DFAL); Dorsal Forearm Right (DFAR); Dorsal Lower Back Left (DLBL); Dorsal Lower Back Right (DLBR); Dorsal Thigh Left (DTL); Dorsal Thigh Right (DTR); Dorsal Leg Left (DLL); Dorsal Leg Right (DLR)

Thermal Symmetry was defined as the ‘degree of similarity’ between two ROIs, mirrored across the human body’s longitudinal main axes which are identical in shape, identical in size and as near identical in position as possible. The degree of similarity is measured in terms of the respective mean temperatures obtained in the ROIs [35].

The capture protocol consisted of the swimmer being subjected to a 10 min acclimatization period in the pool, maintaining a static position and immersing all parts of the body, except the head. To avoid the negative influence of water in thermograms, the swimmer was quickly dried with microfiber towels, avoiding any friction (Fig. 6.5).

Fig. 6.5 Example of participants drying without any friction using microfiber towels

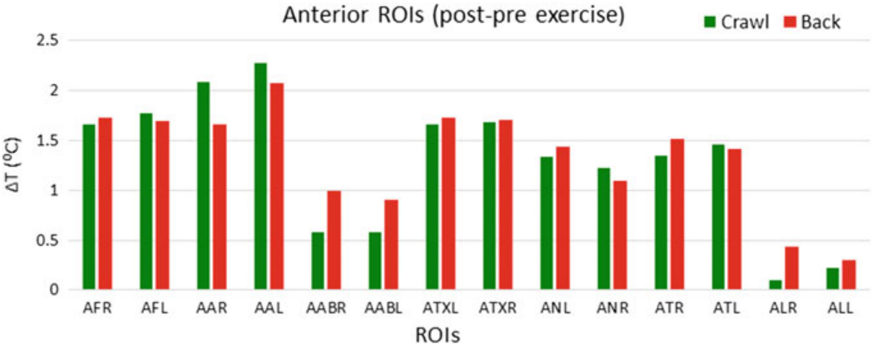


Fig. 6.6 Anterior half-body views regions of interest variation post-pre exercise for both swimming techniques. Anterior Forearm Right (AFR); Anterior Forearm Left (AFL); Anterior Arm Right (AAR); Anterior Arm Left (AAL); Anterior Abdomen Right (AABR); Anterior Abdomen Left (AABL); Anterior Torax Right (ATXR); Anterior Torax Left (ATXL); Anterior Neck Right (ANR); Anterior Neck Left (ANL); Anterior Thigh Right (ATR); Anterior Thigh Left (ATL); Anterior Leg Right (ALR); Anterior Leg Left (ALL)

Regarding the differences in temperature distribution associated with exercise. In all studied regions the temperature variation was greater than zero, which indicates an increase in skin temperature, as can be seen in Fig. 6.6 for anterior ROIs of half-body views in both swimming techniques, and in Fig. 6.7 for posterior ROIs.

The regions with higher temperature increase, for both techniques, are the upper limb (arm and forearm) and upper trunk region (thoracic, upper back and middle back). Although the abdomen and lower back are located in the trunk, they do not indicate significant differences in temperature, as well as, in the neck and leg regions. Example full-body view images, including pre and post swimming technique exercise) are presented from Figs. 6.8, 6.9, 6.10, 6.11, 6.12 and 6.13.

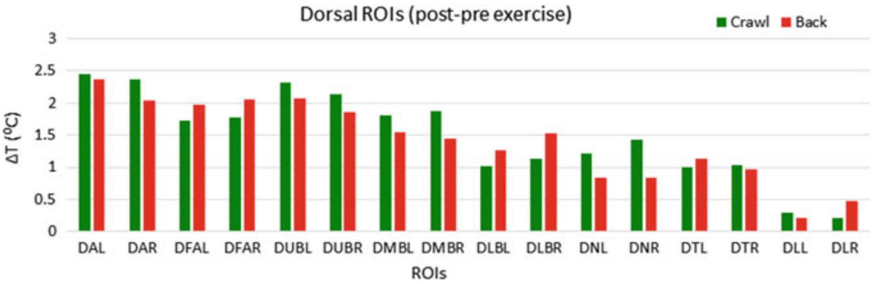


Fig. 6.7 Dorsal half-body views regions of interest variation post-pre exercise for both swimming techniques. Dorsal Arm Left (DAL); Dorsal Arm Right (DAR); Dorsal Forearm Left (DFAL); Dorsal Forearm Right (DFAR); Dorsal Upper Back Left (DUBL); Dorsal Upper Back Right (DUBR); Dorsal Middle Back Left (DMBL); Dorsal Middle Back Right (DMBR); Dorsal Lower Back Left (DLBL); Dorsal Lower Back Right (DLBR); Dorsal Neck Left (DNL); Dorsal Neck Right (DNR); Dorsal Thigh Left (DTL); Dorsal Thigh Right (DTR); Dorsal Leg Left (DLL); Dorsal Leg Right (DLR)

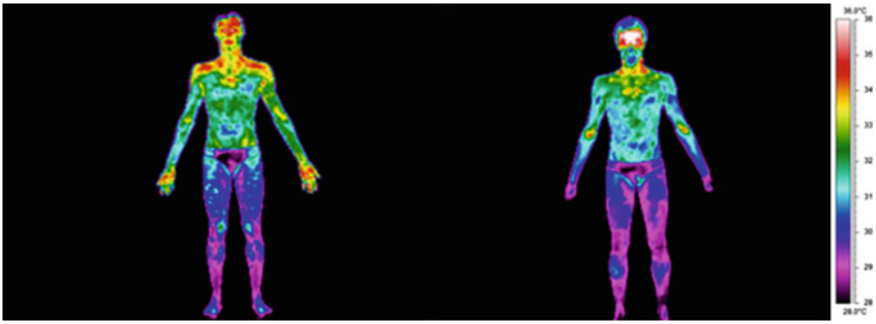


Fig. 6.8 Example of thermal images of pre (*left*) and post (*right*) exercise in full body anterior view

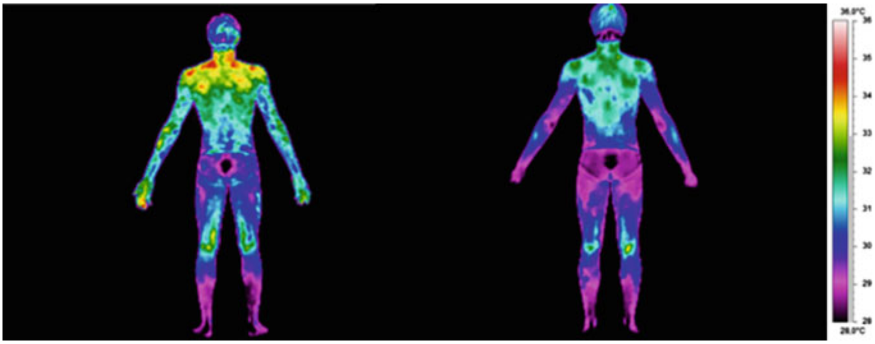


Fig. 6.9 Example of thermal images of pre (*left*) and post (*right*) exercise in full body dorsal view

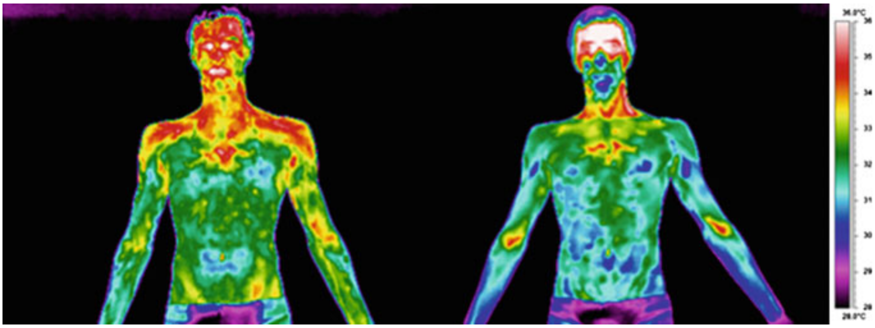


Fig. 6.10 Example of thermal images of pre (*left*) and post (*right*) exercise in half body anterior-top view

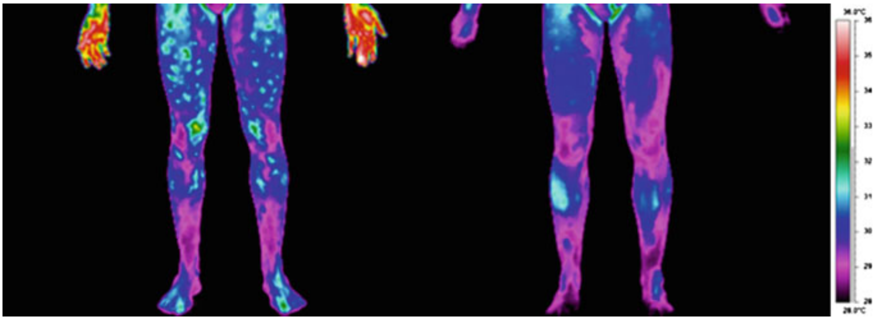


Fig. 6.11 Example of thermal images of pre (*left*) and post (*right*) exercise in half body anterior-bottom view

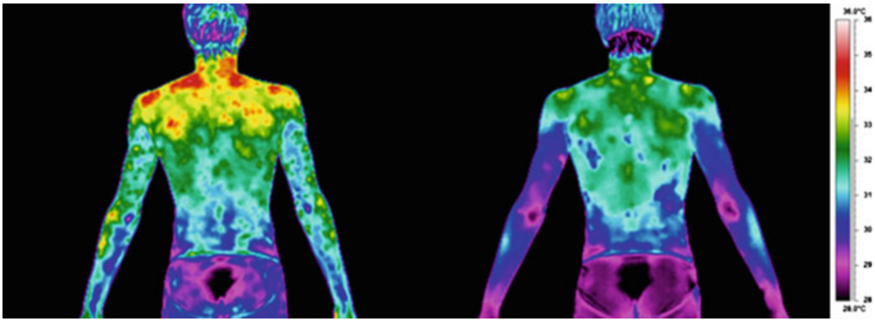


Fig. 6.12 Example of thermal images of pre (*left*) and post (*right*) exercise in half body dorsal-top view

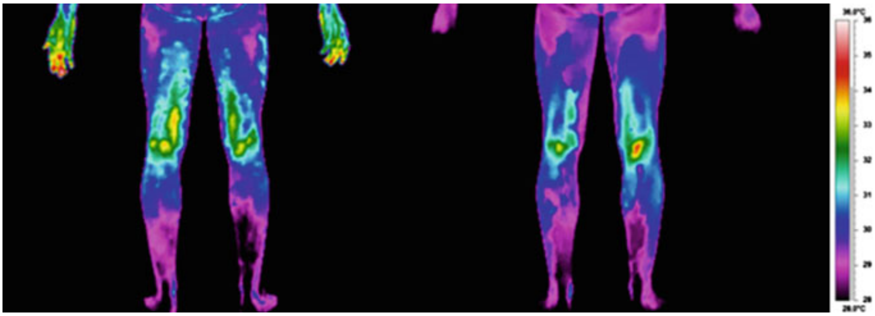


Fig. 6.13 Example of thermal images of pre (*left*) and post (*right*) exercise in half body dorsal-bottom view

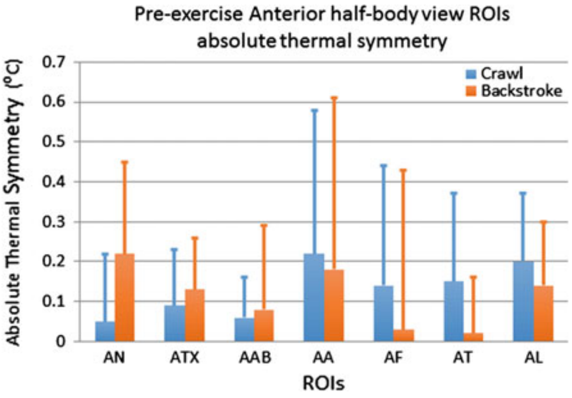


Fig. 6.14 The thermal symmetry absolute values (*left–right* ROI) for both swimming techniques pre-exercise in anterior half-body view. Anterior Neck (AN); Anterior Torax (ATX); Anterior Abdomen (AAB); Anterior Arm (AA); Anterior Forearm (AF); Anterior Thigh (AT); Anterior Leg (AL)

The temperature difference between left and right regions did not exceed more than 0.5 °C for all ROIs. These differences were expected due to the health condition of athletes and also because the swimming techniques performed were symmetrical, only small noticeable changes were found in the arms (for crawl swimming technique) and thighs (for backstroke swimming technique) regions (Figs. 6.14, 6.15, 6.16 and 6.17). There was no significant variation between full and half body view, although the usage of half body views is recommended, because it allow bigger regions of interest and future better discrimination in the case of any pathology.

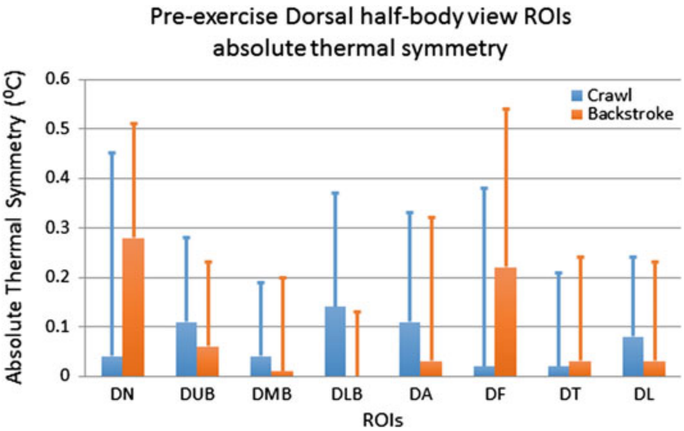
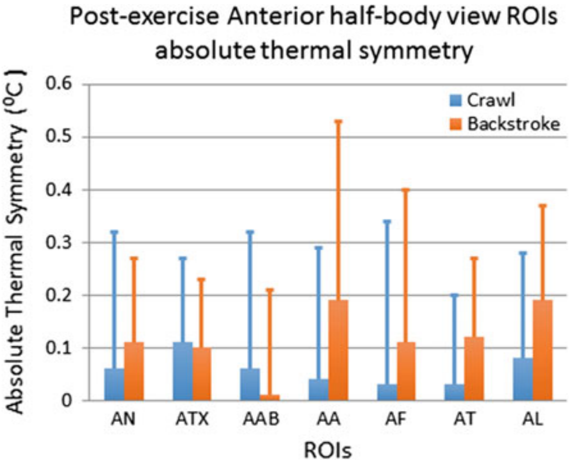


Fig. 6.15 The thermal symmetry absolute values (*left–right* ROI) for both swimming techniques pre-exercise in dorsal half-body view. Dorsal Neck (DN); Dorsal Upper Back (DUB); Dorsal Middle Back (DMB); Dorsal Lower Back (DLB); Dorsal Arm (DA); Dorsal Forearm (DF); Dorsal Thigh (DT); Dorsal Leg (DL)

Fig. 6.16 The thermal symmetry absolute values (*left–right* ROI) for both swimming techniques post-exercise in anterior half-body view. Anterior Neck (AN); Anterior Torax (ATX); Anterior Abdomen (AAB); Anterior Arm (AA); Anterior Forearm (AF); Anterior Thigh (AT); Anterior Leg (AL)



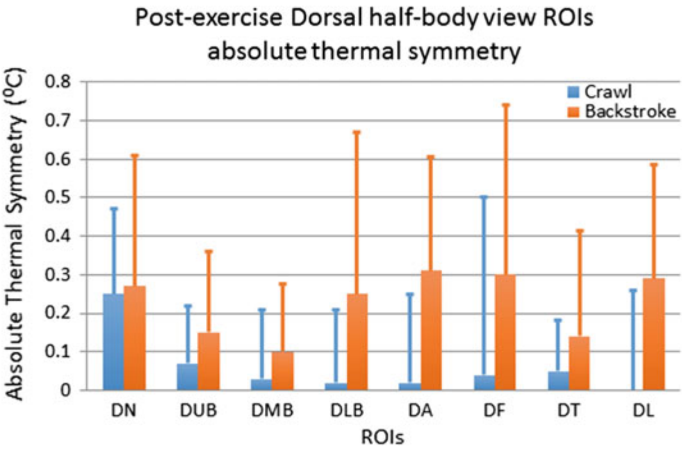


Fig. 6.17 The thermal symmetry absolute values (*left–right* ROI) for both swimming techniques post-exercise in dorsal half-body view. Dorsal Neck (DN); Dorsal Upper Back (DUB); Dorsal Middle Back (DMB); Dorsal Lower Back (DLB); Dorsal Arm (DA); Dorsal Forearm (DF); Dorsal Thigh (DT); Dorsal Leg (DL)

One weakness of this research was not having the participants again inside water during the time of swimming practice for better estimation of the difference between effect of exercise and water immersion.

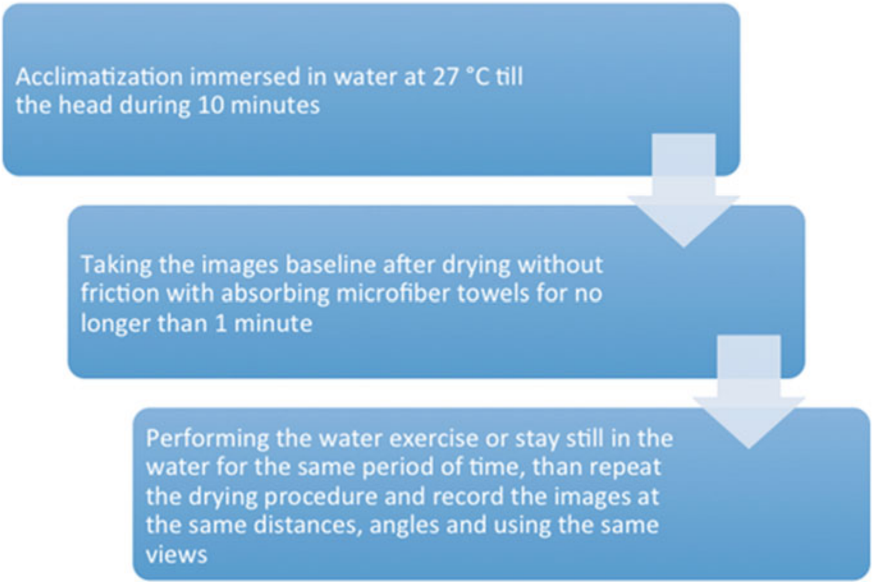
Both swimming techniques significantly increased skin temperature in every ROI ($p < 0.05$), however technique discrimination was not possible since no significant differences were found. From the analysis through the Related-Samples Wilcoxon Signed Rank Test it is possible to observe that there is statistical evidence ($p < 0.05$) for every ROI between pre and post exercise in half-body views. Differentiating swimming techniques through the ROIs and their differences in mean temperatures (post-pre exercise) was not possible due the absence of statistic evidence in avoiding the null hypothesis ($p > 0.05$) with the Independent-Samples Kruskal-Wallis Test. No significant statistical evidence of differences was found between the two studied swimming techniques [10].

6.4 Proposed Methodology for Measuring Skin Temperature in Water Sports

Based in the previously described existing literature, it is known that skin temperature is influenced by several factors. Assessing skin temperature in water sports upon on the internationally accepted human body thermal imaging capture protocols ([23, 36, 37], which specify subject preparation previously and during examination, recording equipment preparation and examination room preparation, there are other intrinsic aspects related with water immersion related exercising.

The athletes should refrain from having a heavy meal, smoking, intaking alcohol or drugs, having tea or coffee in the 2 h before examination, having oil or ointments in the skin, using any jewelry, the recording equipment must be switched on at a safe interval to prevent the startup drift [38], and at the local of examination there should be take actions to prevent any unwanted thermal reflection from any possible source.

Instead of having the acclimatization period at room constant air environment, since the activity takes place in the water, its temperature value has to be constant and depends on the exercise type and research question, but it can be assumed the for most exercises the recommended value would be 27 °C, the subject must stay sill during that period, which is in line with the proposed knowledge [12]. The challenge after acclimatizing in water and after performing the water activity is to dry the skin surface with minimal effect of the whole process, that can be achieved through having minimal contact with highly absorbent microfiber towels, but it has to been done in a minima time (typically 1 min) and using the same direction and speed to reduce the influencing variables. This action with limit the cooling and evaporation effect that water exposure has on skin surface. For a better understanding of the exercise skin temperature influence, it is recommended that the subjects perform a test of staying still at the same condition of the exercise test and during the same time. It is also recommended to use half-body views and keep a distance of about 2 m from the target and use a 90 angle for images capture. The images should be assessed using regions of interest over the muscular areas and



Acclimatization immersed in water at 27 °C till the head during 10 minutes

Taking the images baseline after drying without friction with absorbing microfiber towels for no longer than 1 minute

Performing the water exercise or stay still in the water for the same period of time, than repeat the drying procedure and record the images at the same distances, angles and using the same views

Fig. 6.18 The main points of the proposed methodology for water sports screening with thermal imaging measuring the mean, minimum and maximum temperatures and standard deviations along with the histograms. Based in the literature, distal extremities such as hand and feet should not be considered because of the higher effect that water contact has on them. The Fig. 6.18 resumes the main points of the proposed methodology for water sports screening with thermal imaging.

6.5 Future Research Directions in Water Sports

Future research is needed and suggested for any water activity involving body immersion for a period of time higher than 5 min. In the particular case of swimming, it is required to know if it has any influence in total skin temperature or in the temperature of individual ROIs, the existing studies [6, 8–10, 28–31, 34, 39] give that indication but had a limited number of participants to take wider and accurate conclusions. The influence of the swimmer level and specialization is another issue that needs to be explored, as the influence of age, gender and body composition on the thermal response. The intensity of the swimming technique, the different types of swimming techniques and its effect in skin temperature also needs to be addressed.

An aspect that worth attention is the determination of the appropriate water immersion acclimatization period duration. Other is the ideal method to dry the skin without affecting the exercise effect in the skin temperature.

There is a lot of opportunities in research in this particular field, most till now were based in swimming but there are other water activities that worth attention and interest such as: hydrotherapy, sauna, Turkish bath, diving, water polo, water jogging and any other emerging underwater activity.

6.6 Conclusion

In this chapter the reasons for measuring skin temperature changes during water sports and underlining physiological aspects were outlined. The aspects of the relationship between water contact, exercise and skin temperature were addressed. Example of applications of skin temperature assessment with thermal imaging involving effect of different body masses in water immersion [8], using different types of swimming suits [28], training at different climates [29], assessing different swimming techniques with water acclimatization [6, 10, 39], relating that with energy expenditure [9], comparing yoga and swimming in pregnant women [30] and fifteen minutes in muscle areas after breaststroke swimming [31, 34]. All of these research studies involved small samples but presented interesting and promising results.

A new investigation methodology for thermal imaging screening in water sports was proposed based in the previous studies findings. A future challenge can be repeating some of the described applications with larger samples for confirming the initial results and conclusions.

One thing is certain, using standardized medical thermal imaging has proven to be a useful tool to evaluate temperature differences after sports activity and only implementing it, it is possible to contribute for its development, growing usage and credibility, attracting new users.

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Chapter 7
Assessment of Sport Garments Using Infrared Thermography

Damien Fournet and George Havenith

Abstract Sport garments and their properties directly influence the heat exchanges occurring at the interface between the human skin and the environment. Active skin cooling or warming through innovative apparel is more and more developed in training and competition. Infrared thermography can provide original insights into the patterns of skin temperature distribution during exercise that can then be used for clothing design using a bodymapping approach.

7.1 Introduction

Sport garments nowadays represent a necessary element for all types of physical activity across the world. Our ancestors used to run in the most simple attire fighting for survival, escaping from dangers or exhausting animals. Over the course of evolution, clothing has become a cultural as well as a safety requirement following trends of fashion and protecting the skin against potential external aggressors. Specific equipment and clothing have always accompanied the development of ancient and modern sports.

Sport garments manufacturers are engaged in a design process combining aesthetics and various functions in order to meet the sport demand as well as the body needs. Furthermore, there are sometimes some sport federation rules to comply with for authorization in competing events.

Sport garments are at the interface between the human body and the environment and therefore modify the heat and mass transfers occurring at the skin surface [1].

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In this context, clothing interacts with physiological and physical processes impacting skin temperature that can be assessed by infrared thermography. Over the last decade, much attention has been paid to regional thermoregulatory effector responses (e.g. bodymapping of local skin temperatures) in order to adapt the choice and location of material to better meet the body needs [1–4]. Thermal patterns obtained by infrared thermography with high spatial sensitivity become very convenient over contact measurements on the skin for mapping large body regions.

The assessment of sport garments, specifically their impact on the skin using this technique, enables great advances in the field of garment design and its consequence on sport performance and thermal comfort, both for recreational and professional athletes.

7.2 Sport Garments in Exercise Thermoregulation

7.2.1 The 6 Basic Parameters and Heat Balance Equation

Clothing belongs to the six basic parameters [5] contributing to the overall thermal load placed on the human body in a given condition. Air temperature, radiant temperature, relative humidity (rh) and air velocity are the four external determinants defining the environmental conditions. Additionally, metabolic rate (M) determines the amount of heat produced during sport and this must be adjusted for the external work (W) performed on the outside world.

The combination of the parameters determines the potential avenues for heat dissipation towards the environment and heat gain towards the athlete's body.

The human heat balance equation integrates the different physical heat transfers and provides a calculation (7.1) of heat storage at any specific heat production. Clothing influences the intensity of the heat transfers by conduction, convection, evaporation and radiation.

$$S = M - W - E - K - C - R \tag{7.1}$$

Equation 7.1. Heat balance equation. Where S = net heat storage (W m^{-2}), M = metabolic rate (W m^{-2}) W = external work performed (W m^{-2}, positive or negative), E = evaporative heat loss (W m^{-2}), K = conductive heat transfer (heat loss or gain) (W m^{-2}), C = convective heat transfer (heat loss or gain) (W m^{-2}), R = radiative heat transfer (heat loss or gain) (W m^{-2})

Depending on the climate, duration and intensity of the exercise, sport garments can either minimize or maximize these heat transfers with fixed properties or specific active technologies.

The human autonomic thermoregulatory system is able to deal with decreasing or increasing heat storage by triggering a series of effector mechanisms (vasoconstriction/shivering and vasodilation/sweating) in order to maintain core temperature within a safe range. Skin temperature and the signal transmission from skin thermoreceptors also plays a role in the effective effector responses together with central thermoreceptors.

7.2.2 Basic Clothing Properties

The first basic property is clothing insulation (expressed in m^2 K W^{-1} or m^2 °C W^{-1}). This corresponds to the heat resistance offered by the garment to dry heat transfer (conduction, convection and radiation). Insulation is highly dependent on the amount of air trapped in the material (e.g. textile fibres) and this correlates well with material thickness, modulated by fibre diameter [6].

Apparels for sport can be composed of several items organized in various layers depending on the climate. It is important to take into account the still air also trapped in the microclimate between the different layers of the ensemble. This microclimate can be thick or thin depending on the location (e.g. no air gap at the shoulders), the clothing fit or elements to tighten clothing onto the body. Chen et al. [7] observed that thermal insulation was the largest with an air gap of 0.6 cm in windy conditions. Nielsen et al. [8] measured higher local skin temperatures with a tight-fitting compared to a loose fitting inner layer in a 5 and 20 °C environment, advocating for minimizing air disturbance due to movements to maintain insulation.

Wind, posture and body motion are factors that can indeed greatly modify insulation by compressing the garment or by pumping the air between the different layers, therefore reducing the overall heat resistance [9]. ISO 11079 provides calculations on the required clothing insulation to stay in thermal equilibrium depending on the exercise intensity [10]. For example, clothing insulation of 0.155 m^2 K W^{-1} (= 1 Clo unit) would be necessary in a −20 °C environment whilst running.

Nowadays, garment insulation for cold weather sports comes from either goose down (especially in winter jackets) or from synthetic fibres made with hollow cores or air shafts in order to trap still air [11]. Porous aluminium coating/inner lining to reflect body heat or aerogel with high thermal performance for its thickness can also be used [12].

The second basic property is clothing evaporative resistance (expressed in m^2 kPa W^{-1}). It corresponds to the clothing ability to transfer moisture away from the skin surface. The vaporization of liquid sweat occurs at the skin or in the clothing layers [13]. Similar to heat resistance, evaporative resistance depends on material thickness (with its enclosed air) in the case of permeable materials. Coatings, membranes or other treatments on the garment greatly alter the transfer of vapour molecules to the environment. Some waterproof finishes close the fabric pores, therefore preventing external precipitation to wet the body but this also traps sweat inside the microclimate. For thin garments, the fibre characteristics also affect the diffusion properties and modify vapour resistance.

Other properties related to fibre type, yarn type and fabric construction influence heat and vapour transfers by reducing or enhancing parameters such as air permeability or moisture absorption [11]. Nielsen and Endrusick [14] measured the lowest skin temperature for an underwear having an open fishnet structure in a comparison with four other polypropylene knit structures in a two-layer clothing system at 5 °C.

In many different sports, especially in cold environments, a good compromise must be found between heat and vapour resistance. Sufficient insulation must ensure adequate cold protection before the exercise or during resting periods. At moderate to high workloads, heat production can largely exceed heat loss towards the environment and sweating takes place. Vapour resistance should therefore be small to avoid excessive moisture build up. Total clothing insulation was reduced by 20% when moisture content of the underwear was 100% of its dry weight [15] and wet clothing can lead to after chill.

Ventilation impacts the garment microclimate and can contribute to reduce the build up of non-evaporated or condensated moisture. This can occur through natural openings (at the neck, hands and lower end of a shirt or jacket) or specifically designed ventilation openings such as zippers across the torso, under the arms or at the sleeves. The combination of pit zip and side seam openings was the most effective in lowering skin temperature in outdoor jackets at 20 °C [16]. Zhang and Li [17] observed significant differences in mean skin temperature by modifying opening designs of T-shirt worn whilst running in a 25 °C environment. The bellows effect provided by slits in running jackets has found to be beneficial in terms of lowered skin temperature and improved thermal comfort [18, 19]. In situation of lower heat production or in colder environments, the reduced insulation induced by ventilation [20] must be prevented.

Waterproof membranes can be a requirement for outdoor sport garments in order to cope with snow or rain. Adverse weather can potentially lead to hypothermia, especially during long duration events with low heat production, as is the case of recreational hiking [21].

In summary, basic properties of clothing modify the heat exchanges at the skin/environment interface and therefore determine the level of skin temperature in a given environment. Some sports garments however influence skin temperature more actively and to a greater extent of cooling or warming during exercise.

7.2.3 Sport Garments and Skin Cooling

Skin temperature above 35 °C induces a perception of thermal discomfort [22] and has been found to be a critical factor to exercise performance [23]. Many cooling interventions have been explored for sport in hot weather conditions such as water baths, air exposure, drink ingestion, ice application both prior to [24, 25] and after exercise [26]. Practical aspects and cost of these strategies in real use are often questioned. Skin cooling can also be induced by sport garments during exercise with a direct impact on the cardiovascular, thermal and perceptual strain of recreational and professional sport enthusiasts.

Conductive cooling has been used through light-weight vest in different sports [27–29]. Mean skin temperature was significantly lower wearing the cooling jacket in a 32 °C 70% rh environment with an improved exercise time to exhaustion in male athletes [28]. Palm skin temperature was reduced by up to 1.5 °C wearing an ice vest (Flexi Cold Vest, Interspiro Ab, Lidingö, Sweden) made from water-filled cooling elements chilled at −20 °C before the exercise [29]. Neuromuscular fatigue and ventilatory responses were also lowered compared to a control trial with no vest in a 30 °C 40% rh environment leading to an increase of over 20% in running time. The seven male participants reported an improved thermal comfort throughout the exercise protocol [29]. During a 5 km running time trial in a 25 °C, 55% rh environment, master athletes also experienced improved thermal comfort with a cooling vest but performance was similar to the control condition [27]. The HyperKewl vest (TechNiche, Vista, California, USA) soaked with water and placed in the refrigerator (6 °C > 8 h) was worn during the whole time trial and it induced significantly lower skin temperatures especially at the trunk with up to 2 °C difference during the first half of the trial (Fig. 7.1) [27].

The efficiency of the cooling interventions relates to the surface area covered by the cooling garments as well as the ability to ensure a sufficient fit. In previous examples, the body surface area covered was approximately 0.20 m^2.

Conductive cooling has also been specifically targeted at the neck region. Despite its relatively small surface, the neck is an area of high allesthesial thermosensitivity [30, 31] and it can also be cooled effectively with minimal disruption

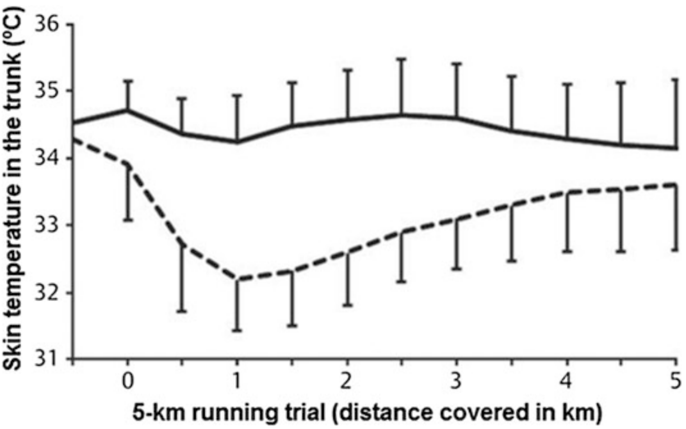

Fig. 7.1 Trunk skin temperature in master athletes during a 5-km running time trial in a control condition (*solid line*) and cooling vest condition (*dashed line*). Figure modifed from Eijsvogels et al. [27]

to sporting actions or attire [32]. Several studies have used a commercially available cooling collar (model CCX, Black Ice LLC, Lakeland, TN) frozen for 24–28 h (at −80 °C) in order to highlight its benefits for performance (time trials, repeated sprints) and perceived thermal strain in 30–32 °C 50–70% rh [32–35]. Neck skin temperature was reduced by up to 18°C during the first stage of exercise.

The integration of phase change materials (PCM) into adjustable packs for jackets represent another option to promote conductive cooling [36–38]. Skin temperature with a PCM vest can be reduced by up to 3–7 °C compared to without a vest in hot environments [36, 38].

Convective cooling was combined with PCM in order to enhance skin cooling in a hybrid system [39]. Four ventilation fans were incorporated into the clothing system with a maximum airflow of 0.012 m^3/s. Local skin temperatures were significantly reduced especially in the upper body (maximum reduction from 1 to 7 °C) compared to the control condition during a walking protocol in a 36 °C, 60% rh. The hybrid system was also effective in improving thermal and wetness perceptions in upper and lower body during both exercise and recovery periods [39].

Evaporative cooling was used through a lightweight garment made of hydrophilic fibres able to sustain water evaporation when wetted and consequently providing skin cooling [40]. During a running protocol in a 30 °C, 44% rh, this garment produced significantly lower mean and local skin temperatures by up to 2 and 5 °C respectively. Cooling the skin before the exercise elicited a reduced sweat loss whereas cooling during exercise reduced heart rate and the rate of perceived exertion. In both interventions, thermal comfort, thermal sensation and wetness perception were improved by mild evaporative cooling on the torso [40].

In the above cooling techniques, the lower skin temperatures enable a greater core-to-skin temperature gradient for dissipating heat from deeper regions of the body. Cardiovascular strain is reduced because less of the total cardiac output needs to be directed towards the skin, allowing more blood to be directed to active skeletal muscle.

All the above studies used only contact sensors to measure skin temperature in various body regions as well as mean weighed skin temperature calculations. Whilst being extremely useful to monitor the changes in skin temperature over time [41], contact sensors can not indicate the total extent of skin cooling over body regions. Moreover, point-to-point variation in local skin temperature can vary by as much as 7 °C over 5 cm [42]. Infrared thermography therefore represents a complementary tool to assess the efficiency of skin cooling especially because surface area is a key factor in the summation of autonomic and behavioural responses.

7.2.4 Sport Garments and Skin Warming

In cold environments, heat production during exercise is often sufficient to maintain total heat balance. However, extremities can be at risk of extensive cooling due to vascoconstriction. The clothing strategy is classically to choose the adequate insulation with multilayer garments including footwear, gloves and hats [43]. Nevertheless, the freedom of movement is key to many sports and increased bulk with increasing insulation should be avoided. Most of the examples below are more related to extreme industrial applications but the principles are now used in sport garments for enhanced local and overall thermal comfort.

Conductive warming through electrical heating was applied on the hands (heating wire on the fingers and back of hands covered by Arctic mitts) and separately on the torso (10 Kapton insulated flexible heaters) [44]. Finger skin temperatures were maintained at 28–35 °C in both conditions but torso heating (at 42 °C) contributed to an 8-time higher finger blood flow in a −25 °C environment.

In a less extreme context (2 °C, 80% rh) and using a walking protocol, Song and Wang [39] observed 2 °C higher skin temperatures at the stomach and back using an electrically heated vest (7 heating pads) compared to the same unheated vest. This was also true with a chemically heated garments composed of 14 non-reusable body warmers (iron powder, activated carbon, water, vermiculite and salt) for approximately the same surface as the heating pads. Both heated conditions induced improved whole body and local thermal sensations.

Conductive warming using PCM garments has been explored with simulation [45] or manikin studies [43] but no human testing to date.

Conductive and convective warming can be obtained through liquid warming garments such as the one designed for spacesuit with tubing over all body regions. This has proven to be effective in elevating skin temperatures especially in the fingers [46].

Some sport garments can also be worn at the end of the warm up phase or during recovery periods such as half time of team sport events. Faulkner et al. [47] demonstrated the benefits of conductive warming of lower leg muscles with heated trousers. This intervention increased local skin temperature and most importantly reduced the fall in muscle temperature (by approximately 1 °C), therefore preserving optimal power contractile properties for subsequent exercise performance. Similarly, Wilkins and Havenith [48] showed that a heated jacket worn between a swimming warm-up and the actual race can increase skin temperature and improve sprint swimming performance (Fig. 7.2).

Similar to cold conditions, infrared thermography could become useful to assess the spatial extent of skin warming in order to evaluate more precisely the efficiency of heating interventions or specific active garments during exercise.

7.3 Infrared Thermography Assessing the Influence of Sport Garments

The microenvironment between the skin and the inner-most layer of clothing affects skin temperature which, in turn, affects thermoregulatory responses. Skin temperatures should accurately assess the effectiveness of a clothing ensemble [11].

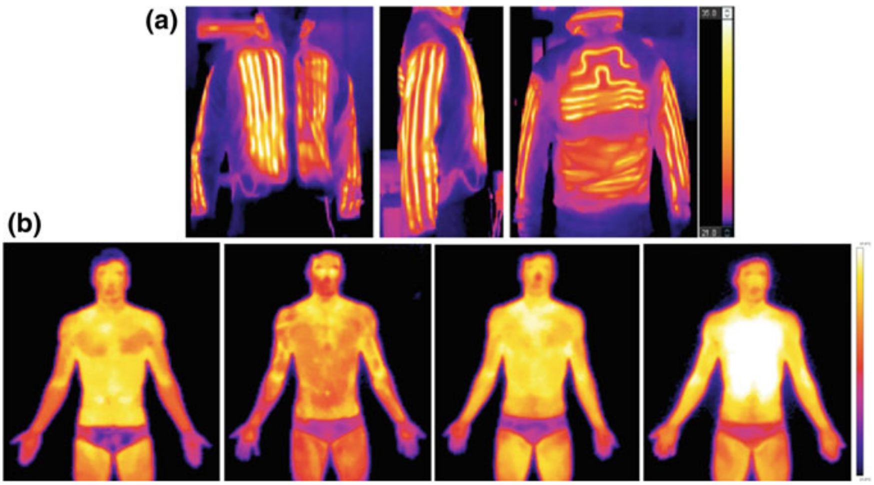

Fig. 7.2 **a** Thermography of the heated jacket. Figure obtained from Wilkins and Havenith [48]. **b** A sample of upper body thermograms from left to right: prior to warm-up, after warm-up, after recovery period for control and for heating. Temperature range 21–37 °C

Moreover, core temperature is rarely modified by sport garments and depends to large extent upon metabolic heat production. The concept of "thermal envelope" has then been suggested in order to evaluate the influence of sport garments in ecologically valid sports-related exercise protocols [49]. It refers to upper and lower limits in mean body temperature (from mean skin and core temperatures) elicited by clothing assemblies that could be worn under a given environmental conditions. Measuring skin temperature in various locations, especially in cool environments [50], is therefore highly important for this approach. Though infrared thermography can not track skin temperatures over time in clothed subjects, it provides the benefit of measuring large body surfaces with high-spatial resolution. Previous research has pointed out that skin temperatures and distribution immediately after undressing are the same as those which existed under the clothing [51, 52]. With careful data collection and standardized undressing procedures, this opens a wide area of testing the influence of many kinds of sport garments. The current knowledge in this field is presented with key examples in specific sports.

7.3.1 Assessment of Running Wear

Many studies have investigated skin temperature distribution of semi-nude runners using infrared thermography [4, 53–56]. Apart from the pioneering work from Clark et al. [54], no studies reported whole-body thermograms as they focused on specific body parts to understand the underlying mechanisms modifying skin temperatures between physiological (skin blood flow, muscle activation, body composition) and external factors (air and radiant temperature, air velocity, relative humidity). Fournet et al. [3] provided the first average whole-body thermograms based on a specific image processing technique [57] able to combine several thermograms of participants with a variety of body dimensions.

A quantitative and qualitative data analysis was provided on male and female runners with a special focus on the link between skin temperatures and skinfold thickness variations [57].

Using the same approach, Fournet [51] explored the thermal patterns of clothed runners at different stages of the exercise protocol. Twelve physically active males performed a 40-min running bout at 70% $VO_{2\max}$ in a 5 °C, 50% rh environment with frontal wind at 5 $\mathrm{m\ s^{-1}}$. This was preceded by 5 min standing prior to exercise and followed by 10 min post-exercise recovery also standing on the treadmill with 2.8 $\mathrm{m\ s^{-1}}$ frontal wind. Participants were wearing a one-layer tight-fitting winter long sleeves top and tights (Kalenji Isolate 4000, DECATHLON, France). Infrared thermography assessment was obtained at 4 different stages: prior to exercise (PRE), after 10 min of running (RUN10), after 40 min (RUN40) of running and after 10 min of recovery (POST); following a strictly controlled and short undressing procedure away from the wind. Whole-body thermograms ($n = 12$) are presented at stage RUN40 for the anterior and posterior body (Fig. 7.3).

Skin temperature underneath clothing was colder in regions such as the abdomen, pectorals, thighs, triceps, patella, neck and cheeks. They corresponded to regions deeply or poorly perfused, with large fat or muscle insulation, highly exposed to air velocity. The warm regions were located in the upper chest, spine, inner thighs, calves, elbow crease, popliteal fossa and orbits. They corresponded to regions with either high perfusion, low fat or muscle insulation and the natural creases of the human body where cross radiation exists between close surfaces or when surfaces are directly in contact.

A Y-shape of colder skin temperatures was noticeable over the anterior torso (pectoral and abdomen) and a Y-shape of warmer temperatures over the posterior torso (upper back and spine). Fournet [51] provided the general hypothesis of the compromise between the superficial blood flow and body characteristics (morphology and composition) to explain the skin temperature variations across the body. Hot spots in the upper chest, neck and upper back were strikingly in line with brown fat deposits in infants. As brown fat has been observed in adults especially in lean persons exposed to cold [58], it could be postulated that these regions contributed to specific warm spots due to their high vascularization and not necessarily due to their associated local thermogenesis.

Interestingly, mean skin temperature was similar in the clothed condition at 5 °C compared to the semi-nude condition at 10 °C [3]. The thermal patterns were almost identical between the conditions except for the warmer skin temperature at the upper chest and forearms (clothed) and at the calves and posterior legs (semi-nude). This could imply that heat dissipation is favoured close to heat production in the nude moving lower limbs. On the other hand, heat could be conveyed

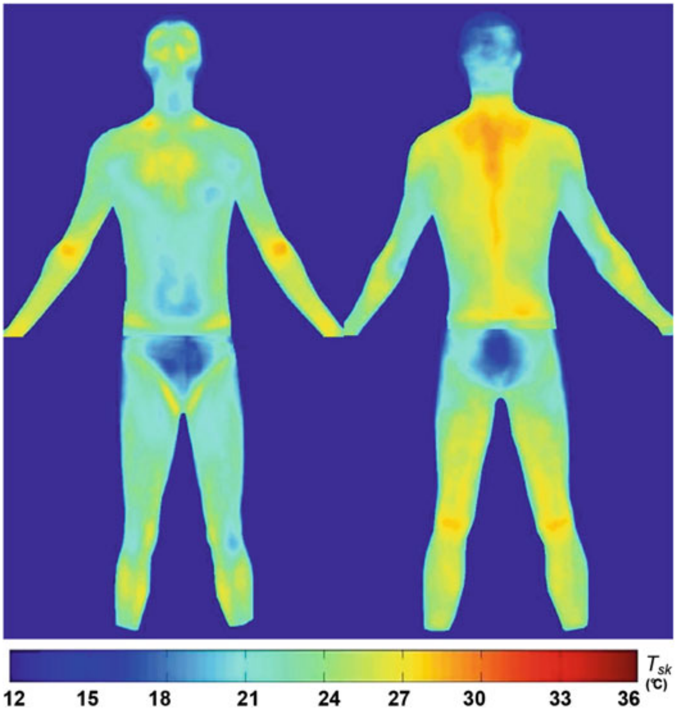

Fig. 7.3 Anterior (*left*) and posterior (*right*) group averaged whole-body maps of skin temperature after 40 min of running at 70% VO_{2max} in a 5 °C, 50% rh environment with uniform clothing insulation. Figure adapted from Fournet thesis [51]

back to the heart and then dissipated when quitting the aortic arch (upper chest) more intensively in a clothed condition.

Roberts et al. [4] investigated the thermoregulatory responses of 7 males wearing different base-layer garments during an intermittent running protocol. The base-layer hot was claimed to keep the wearer comfortably cool during exercise in warm environment whereas the base-layer cold garment was claimed to keep the wearer warm in cold conditions. These two garments with good wicking properties were compared to a 100% cotton base layer and bare-chested condition. Two running bouts lasting 23 min were repeated in a 20 °C, 50% rh environment on a treadmill with speeds varying from 6, 12 and 15 km h^{-1}. Mean, maximum, minimum skin temperatures were assessed based on the front and back torso area covered by the garments.

At the end of exercise, core temperature was similar between clothing conditions. On the other hand, mean skin temperature over the torso was the lowest in the bare-chested condition (28.5 ± 0.8 °C) followed by the base-layer hot (29.1 ± 0.4 °C). These were significantly lower than in the base-layer cold (29.8 ± 0.8 °C) and the 100% cotton garment (29.8 ± 0.8 °C). The thermoregulatory responses was associated with improved thermal comfort in bare-chest and base-layer hot condition compared to base-layer cold and cotton. Roberts et al. [4] postulated that this could be due to the low moisture retention in the lightweight base-layer hot (small yarn diameter, more interstices) therefore reducing skin wettedness, an indicator of thermal discomfort [6].

Some similarities in the thermal patterns were found such as the larger areas of higher temperature over the sternal region and the external oblique muscles of the abdomen. Thermal peaks could be observed in each condition and this is in line with previous work on semi-nude participants [55, 59] in connection with cutaneous perforators veins transferring blood from deep active regions [60]. The differences in evaporation and skin contact especially when garments became saturated could explain the significant differences between the conditions [4].

To date, this has been the only study exploring different clothing composition using infrared thermography to evaluate its impact on skin temperatures and the overall thermal pattern after running.

Priego Quesada et al. [61] conducted a specific study to point out the effects of graduated compression stockings on skin temperature after running. Forty two participants (29 males and 13 females) performed two running tests in a 24 °C, 50% rh lasting 30 min (10 min of warm up and 20 min at 75% of maximal aerobic speed) with and without compression in the lower leg. They hypothesized a direct influence of the covered body regions with extra insulation as well as a potential effect on areas with no garment contact. A quantitative analysis was performed based on a definition of several regions of interest (Fig. 7.4).

It was shown that running with compression stockings increased skin temperatures by 0.04–0.91 °C which could be due to the garment insulation. Moreover, skin temperatures in regions not covered by the stockings (vastus lateralis, abductor, semitendinosus) increased by 0.01–0.52 °C and it could be explained by a greater superficial perfusion induced by the lower limb coverage.

The knowledge of the thermal patterns under running apparels [4, 51, 61] could be extended to a myriad of clothing conditions and exercise types (continuous, intermittent, sprints, short/long distances) in order to map the similarities and differences in skin temperature distribution.

7.3.2 Assessment of Sports Bras

The influence of sports bras has mainly been studied in the field of biomechanics with the aim of reducing breast movement as well as exercise-related breast pain [62, 63]. This led to recommendations for the use of well-fitted and supportive sports bras while exercising. Ayres et al. [64] were the first to specifically investigate the influence of this clothing layer and composition on skin temperatures.

Eight females with C-cup breasts performed a short duration exercise protocol (20 min) in a 27 °C, 46% rh environment [64]. The protocol included a warm-up walk at 4 km h^{-1} (1% gradient) followed by 5 countermovement jumps and

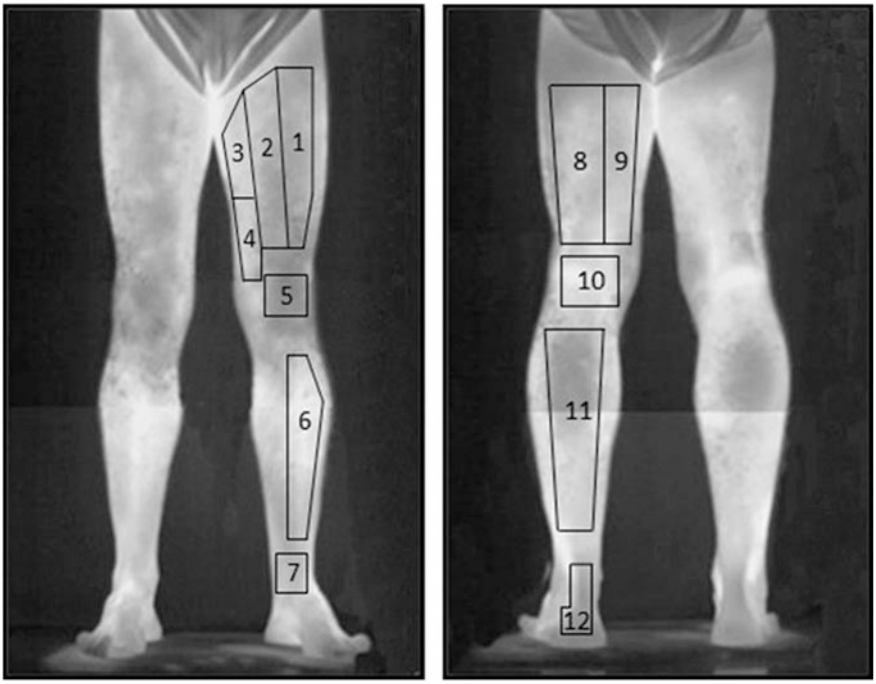

Fig. 7.4 Regions of interest for the evaluation of graduated compression stockings. *1* Vastus Lateralis. *2* Recture femoris. *3* Abductor. *4* Vastus medialis. *5* Knee. *6* Tibialis anterior. *7* Ankle anterior. *8* Biceps femoris. *9* Semitendinosus. *10* Popliteal. *11* Gastrocnemius. *12* Achilles. Figure obtained from Priego Quesada et al. [61]

5 maximum effort agility "T" test followed by 8 min of running at 10 km h^{-1}. They were either wearing a composite sports bra (65% Nylon, 22% Polyester 13% Elastane, Under Armour, Stability, USA) or polyester sports bra (100% Polyester, Under Armour, Strength, USA). The bare-breast and abdomen skin temperatures were assessed using infrared thermography before and immediately after exercise. Reflective markers were taped onto the skin in order to standardize the quantitative analysis with different regions of interest as shown on Fig. 7.5. The temperature of the left and right breast was averaged for each image. Results indicated that breast skin temperature was reduced to a lesser extent than abdominal skin temperatures (−0.6 vs. −2.1 °C) in both bra conditions demonstrating the reduced evaporative heat loss caused by the bra. This effect of insulation provided by the bra on breast skin temperature was also observed by Fournet et al. [3] during a running protocol in females.

In Ayres et al.'s study [64], bra composition had a significant influence on skin temperatures with a larger overall decrease in the polyester (−1.5 °C) compared to the composite sports bra (−0.9 °C). While bra comfort and bra fit were similar between conditions, participants reported greater thermal comfort in the polyester

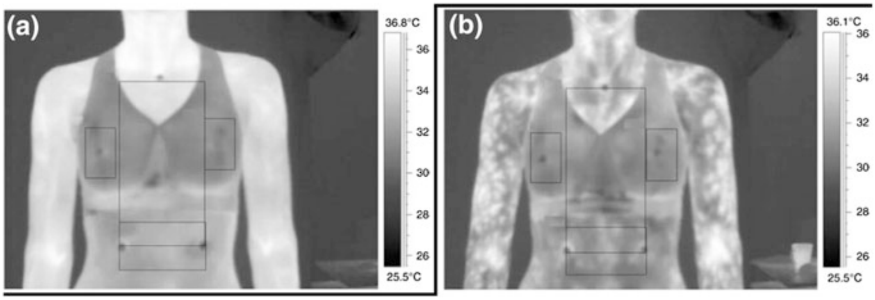

Fig. 7.5 Thermograms of bra and skin temperatures of a participant wearing the composite bra before (**a**) and after (**b**) exercise in the thermoneutral condition. Regions of interest are highlighted. Figure obtained from Ayres et al. [64]

than in the composite bra. There was yet no significant correlation between thermal comfort and pre-post skin temperatures with large variability in comfort responses. Ayres et al. [64] also pointed out that both bras displayed a similar shape and coverage. Nevertheless, there was a mesh section in the composite bra at the back and this corresponded approximately to an open uncovered section in the polyester bra.

Several future directions in bra ergonomics were suggested with the influence of additional clothing layers, the contribution of other physiological factors (hydration, heart rate, core temperature) on breast thermal comfort. The results also highlighted the importance of optimising the design of sports bras in order to facilitate the cooling ability of the skin. These changes can improve thermal comfort which may also lead to differences in athletic performance [64].

7.3.3 Assessment of Hiking Ensembles

Hiking is a popular recreational activity with large participant numbers varying widely in terms of age, gender and hiking experience [65]. In severe cases, hypothermia can occur during hill walking and this has been associated with reduced clothing insulation (cold, wet and windy weather) and progressive fatigue due to the inability to compensate heat loss with heat production [66–68]. Adequate clothing ensemble is therefore required in changing outdoor settings (water repellent, minimal condensation) along with good pacing strategy to allow for sufficient energy expenditure. Apart from Pugh [69], no studies have assessed body temperatures and associated thermal comfort of hikers facing non-adverse conditions. Fournet et al. [70] replicated the thermal strain of a normal day hike in cool conditions within the laboratory and integrated infrared thermography to assess skin temperatures under clothing over the whole-body at different stages.

Eight males and eight females performed a simulated morning walk 2*30 min of uphill walking (15% gradient) at 55% VO_{2max} followed by 15 min seated rest at the top (with 10 km h^{-1} wind) followed by 30 min of downhill walking (15% gradient) at 20% VO_{2max} [70]. In the first half of the ascent, participants were wearing trousers (Forclaz 900, Quechua, Decathlon, France), T-shirts (Forclaz Quechua, Decathlon, France), fleece (Florclaz 50, Quechua, Decathlon, France), sports bra for females (Sportance, Kalenji, Decathlon, France) as well as backpack with 10% body mass (Forclaz 50L, Quechua, Decathlon, France). In the second phase of the ascent, they removed the fleece layer. Environmental conditions were changed from 5 °C, 50% rh to 15 °C 60% rh during the first 30 min to mimic real life conditions in a condensed manner.

Mean skin temperature was significantly lower for females compared to males (−0.7 °C) during the uphill and resting stages [70]. Locally, skin temperature changes were more pronounced in females compared to males, except for the legs. Notably, anterior arm skin temperatures fell by 3 °C during the uphill phase in females and by 2 °C in males. Females had significantly colder thermal sensation at the start, a less humid wetness perception after 30 min of ascent, and they had larger thermal discomfort at rest when exposed to wind.

Group-averaged thermograms were obtained at each stage using the image processing method described by Fournet et al. [57]. The relative maps of skin temperature distribution enabled a direct comparison between males and females despite differences in mean skin temperature (Fig. 7.6).

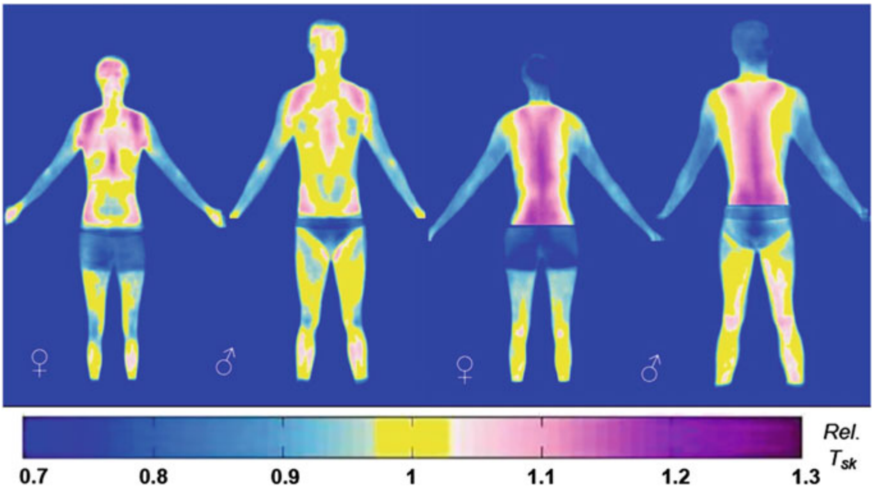

Fig. 7.6 Anterior (*left*) and posterior (*right*) group averaged relative whole-body maps of skin temperature for females (♀) and males (♂) after 60 min of uphill walking at 55% VO_{2max} in a 15 °C, 60% rh environment with uniform clothing insulation. Thermograms are normalised to mean skin temperature, with a value of 1 equal to mean skin temperature in both groups. For example, 0.7 corresponds to 0.7 times mean skin temperature. Figure adapted from Fournet thesis [51]

Patterns of skin temperature distribution were highly similar between males and females. This is in line with a study on unclothed male and female runners [3]. Interestingly, no correlation of the temperature distribution with local skinfold thickness was observed suggesting that other factors than fat distribution are responsible for the skin temperature distribution.

Main consistencies in the thermal patterns were related to the warmer upper body versus lower body, a V or Y shape of warmer skin temperature over the anterior torso, the warmer lower leg over active muscles, the colder arms due to the absence of clothing insulation (short sleeve T-shirt during the second ascent phase). The influence of the backpack was clearly noticeable with higher skin temperatures in localised body regions in contact with the shoulder straps, the belt (with abdominal pads) and the upper/lower back which seemed more pronounced in females (Fig. 7.6).

Interestingly, males performed an additional trial without backpack at a similar heat production. The quantitative analysis (based on specific control points) highlighted the magnitude of these local effects reaching a maximum of 3 °C higher skin temperatures in the lower back for the backpack condition [51].

The use of infrared thermography for the assessment of sport garments described in the literature remains limited to a few number of studies. In certain thermo-physiological studies where rapid temperature changes are expected, it seems inadequate unless the area of interest is not located under clothing. On the other hand, infrared thermography and specific processing methods can help in the evaluation of clothing interventions such as warming or cooling jackets [48, 71], different garment composition [4, 64], the addition or subtraction of clothing layers [51, 61] or other sport equipments [51, 72]. The main advantage of mapping large body surfaces is rarely exploited as quantitative analysis are often limited to defined regions of interest (e.g. Ayres et al. [64]) not necessarily taking into account the natural pattern of skin temperature distribution. The understanding of these patterns in connection with clothing properties, the type of sport and external determinants (e.g. wind) can be extremely useful to better adapt the design, the choice of material of sport garments using a bodymapping approach for improved thermal comfort and exercise performance.

7.4 Infrared Thermography and Bodymapping Sport Garments

7.4.1 Design and Evaluation of Bodymapping Garments

A bodymapping approach refers to the knowledge of biological and/or sensorial responses associated with several body regions exposed to the same stimulus or condition. Havenith et al. [1] exposed the principles of this bodymapping approach in the field of thermal comfort and clothing ergonomics. Regional clothing adaptation can be made according to the regional knowledge of skin temperature, sweat production/skin wettedness and the regional skin sensitivities to temperature and wettedness [1]. Many bodymapping studies on these parameters have been performed using different techniques, with local thermal stimulations [73–76], local sweat collections with absorbent pads [1, 77, 78], simultaneous contact sensors [30, 79] and infrared thermography for skin temperature mapping [3, 51, 57, 70].

The combination of the different maps and their relevance according to the exercise type and environmental conditions is determinant for clothing manufacturers. This may lead to improved thermal-wet perceptions, more efficient heat loss or preservation, reduced sweat loss that can all contribute to exercise performance.

Wu et al. [80] attempted to use this kind of approach by combining skin temperatures and several thermal-wet perceptions in connection with the evaluation of 10 kinds of hygroscopic fibres. They developed a T-shirt assembled with 4 fabrics matching regional requirements.

The choice and position of fabrics can be based on various bodymaps. Yet, in the overall garment construction, garment fit plays a crucial role by modifying the heat and mass transfers between the skin and environment. Some studies have therefore performed quantification of the volume and size of air gaps determined by garment fit [81–83]. They have highlighted the uneven distribution of air gaps layers using 3D body scanners. Zhang et al. [83] combined this assessment with infrared thermography of clothing surface temperatures [83] (Fig. 7.7).

They found that air gap usually have larger thickness in concave areas (lumbar region) and smaller thickness in convex areas (hips, shoulders) formed by the human skeleton and muscles. Clothing surface temperature decreases with increasing air gap thickness up to a critical thickness of 15 mm upon which natural convection occurs [83]. Based on this local knowledge, a revised pattern was designed with additional cover cloth on the shoulder and waist darts in the back waist region. This led to an improved thermal insulation of the new garment as measured on a thermal manikin.

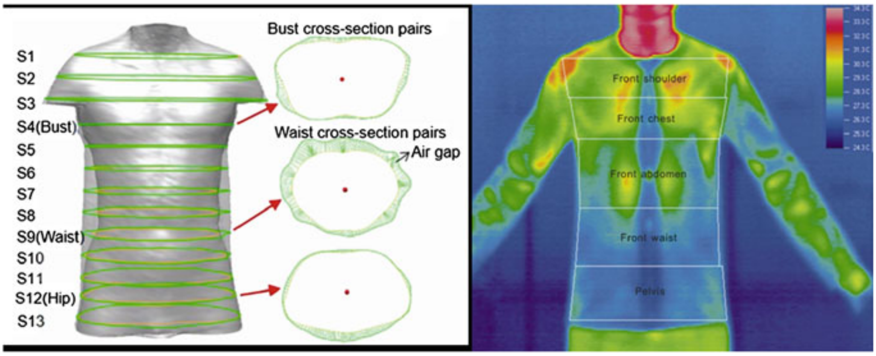

Fig. 7.7 3D scanner analysis with the selection of cross section pairs (*left*) and clothing surface temperatures (*right*) with regions of interest for the same garment. Figure obtained from Zhang et al. [83]

In the five-level system for the analysis of the physiological properties of textiles and garments [84], manikin testing represents a key level in the assessment of sportswear. It provides overall heat and vapour resistances as well as localised resistances depending on the number of body segments. Kicklighter et al. [85] reported that the scientific knowledge on bodymapping sportswear engineering has lagged far behind commercial practices of these garments.

A few studies have analysed the thermal properties of bodymapping sportswear on sweating manikins [17, 86, 87] as well as their implications for physiological and perceptual responses through human testing [3, 17, 80, 83].

The presence of mesh or openings at the two vertical side seams was found to be ideal for ventilative cooling based on manikin testing in a constant temperature mode [17, 86]. Wang et al. [87] used a manikin in thermoregulatory mode and demonstrated that bodymapping sportswear did not provide global advantages (mean skin and core temperature) but local improvements in heat and vapour transfer were beneficial for local thermal perceptions, especially with a modular system.

Wu et al. [80] measured lower thermal and sticky sensations using a bodymapping T-shirt with 25 females at very low exercise levels in a 24 °C 55% rh environment. Zhang and Li [17] observed lower skin temperatures with mesh fabrics at the front torso (vertical) for 6 males running at 40% VO_{2max} in a 25 °C, 50% rh environment. There were no differences in perceptual responses between all bodymapping garments varying in mesh location but thermal comfort was significantly improved compared to a no-mesh control condition [17]. Lastly, Wang et al. [83] reported significantly improved physiological responses (lower mean skin and core temperature, mean torso temperature and heart rate) and local thermal sensations with a modular tight-fitting bodymapping kit worn by 8 males running at 10 km h^{-1} in a 30 °C 40% rh environment.

In warm to hot environment, these bodymapping studies focused on adapting the wicking, air permeability and vapour resistance of fabrics assembled in sport garments mainly based on knowledge of sweat production and efficient garment construction. Skin temperatures were measured by local contact sensors potentially over-estimating or under-estimating the impact of specific fabrics locally [42]. Infrared thermography could bring more insights into the real efficiency of bodymapping sport garments and provide directions into improving their benefits for thermal comfort and exercise performance.

7.4.2 From Thermograms to Bodymapping Garments

Infrared thermography can be used for whole-body temperature mapping [2, 3, 51, 57, 70] and this knowledge can be translated into bodymapping sportswear. Havenith et al. [1] suggested that placing extra insulation on the specific cold body regions would be beneficial for overall thermal comfort whilst targeting the warm regions could prevent unwanted heat loss. The natural whole-body distribution of temperature is required for this kind of strategy towards improved garment, especially for cold weather sports or activities. Furthermore, this distribution can also serve in the heat to maximise heat loss or for targeted cooling interventions, though regional skin temperatures become almost similar above 30 °C air temperature during exercise [88].

Domina et al. [89] described a method based on 3D scanning and infrared thermography in order to provide individual thermal profiles. Image registration techniques are used to transform 2D thermograms onto 3D scans of the same person (Fig. 7.8). They suggested that this could lead to bodymapping garments customized by function (heat dissipation or preservation) and by fit necessary for designers and product developers. Domina et al. [89] mentioned potential improvements in performance as well as cost savings due to more specific placing of fabrics or finishes. Preliminary results using this method (bodymapping garment designed for the upper body) were promising for improved thermal comfort and reduced skin temperature changes during a short duration exercise (Harvard Step test) on 2 males in a 2 °C but not in a 29 °C environment [90].

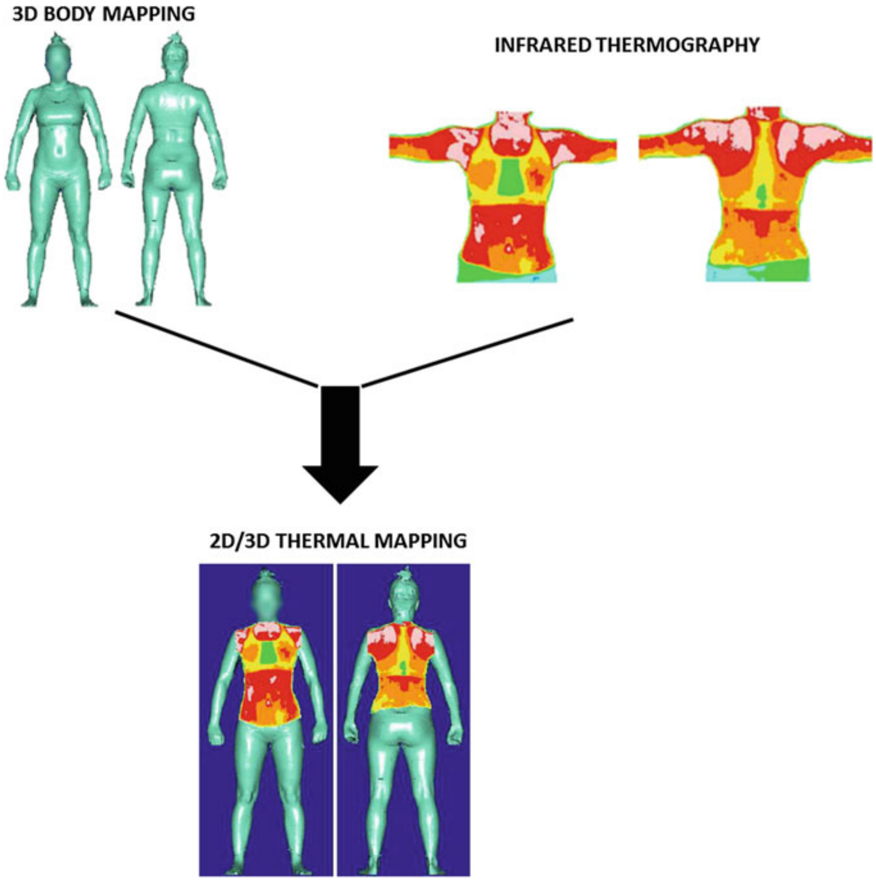

Fig. 7.8 2D/3D thermal mapping method described in the study of Domina et al. [89]. Figure adapted from Domina et al. [89]

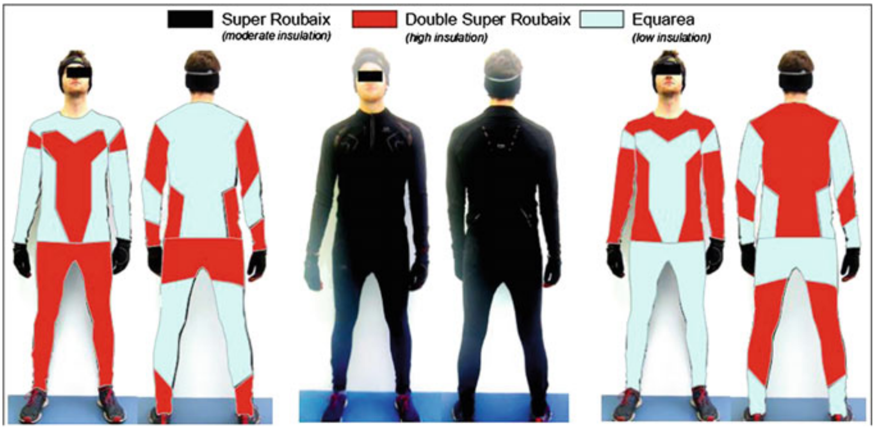

Fig. 7.9 Presentation of the 3 clothing ensembles (C, U and W). Normal colour was black for all ensembles. Figure adapted from Fournet thesis [51]

Fournet et al. [2] investigated for the first time the suggestion by Havenith et al. [1]. Bodymapping sport garments were designed based on the natural distribution of skin temperature distribution under clothing obtained by infrared thermography whilst running in the cold (see Fig. 7.3). Thermal patterns were divided into 2 isotherms of skin temperatures to decide about the body regions where clothing insulation was modified. Two levels of insulation (high and low) were applied within the running ensemble and compared to an ensemble where moderate insulation was uniformly distributed (Clothing U). Clothing C was designed to add insulation in the naturally cold regions, Clothing W in the naturally warm regions (Fig. 7.9). All clothing ensembles had similar overall clothing insulation (0.7 Clo).

Twelve males performed a 40-min running bout at 70% VO_{2max} in a 5 °C, 50% rh environment. Overall thermoregulatory responses were not affected by the type of clothing (similar mean skin and core temperature). Regional skin temperatures assessed by infrared thermography were strongly affected due to the different distributions of insulation. Clothing U led to a natural skin temperature distribution whereas Clothing W reinforced this distribution and Clothing C significantly reduced skin temperature variations across the whole body (creating a more homogenous pattern). High insulation induced 2–2.5 °C higher regional skin temperatures compared to thinly insulated condition irrespective of placing the insulation on naturally "warm" or "cold" regions (Fig. 7.10). High insulation in W had a significant negative impact on thermal comfort in the upper back and arms as they were perceived warmer and wetter compared to clothing C and U. Overall, there were more positive comfort ratings for C suggesting the benefits of reducing skin temperature contrasts between regions [2].

Further studies are required to understand the influence of bodymapping sportswear in the cold. Manipulation of local heat resistances could be mixed with the manipulation of vapour resistances to maximise comfort and performance in

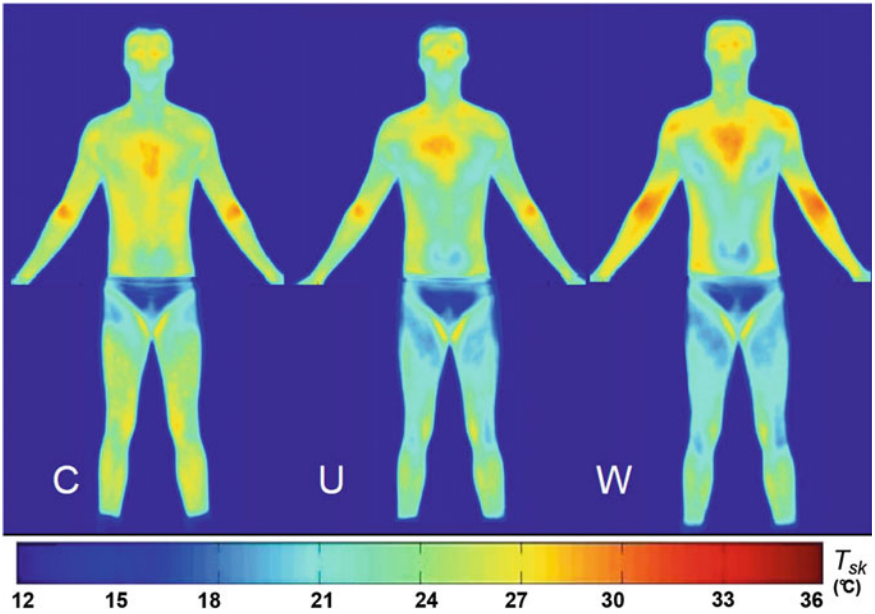

Fig. 7.10 Anterior group-averaged whole body maps of skin temperature for clothing C (covering the cold regions), clothing U (uniform moderate insulation) and clothing W (covering the warm regions) for 12 males after 40 min of running at 70% VO_{2max} in a 5 °C environment. Figure adapted from Fournet thesis [51]

moderate to high intensity exercise where sweat production and skin wettedness can be detrimental [6]. Fournet [51] also presented modular systems allowing easy and quick behavioural adjustments of the local heat loss by the wearer to take into account the wide variety of weather conditions (especially in outdoor sports) and the potential variations in exercise intensity due to pacing or the sport demand.

Infrared thermography was the perfect tool to assess the efficiency of the clothing intervention and can be promising in both evaluating normal patterns and deviations from these patterns with bodymapping sportswear [2].

7.5 Conclusion

Infrared thermography has been used only to a small extent in the field of sportswear ergonomics. There are yet numerous examples where this method could be used in addition to contact sensors for the measurement of skin temperatures. Some challenges need to be overcome regarding processing time, method and speed of clothing removal as well as standardised processing techniques for the analysis of thermograms. Nevertheless, the individual qualitative and quantitative information obtained by infrared thermography can be extremely valuable to assess the efficiency of sports garments at the skin interface (warming, cooling, reducing temperature contrasts), consequently leading to improvements in thermal comfort and/or exercise performance.

Athletes or coaches may benefit from the development of external device (such as drones with integrated infrared cameras) able to monitor the uncovered body part (hands and face) of sporting situations in order to track/predict emotional and physiological changes [91]. With increasing wearable sensors integrated into clothing, one can imagine sport garments that could automatically adapt to these changes taking also into account weather conditions, heat production and the skin temperature/wettedness.

Infrared thermography can also help in the development of more customized sport garments where individual temperature patterns can be useful for targeted heat loss or preservation. High resolution thermograms can display the exact positions and variations of muscle perforators where substantial heat is being released. Favouring the extraction of heat or cooling intensely these spots may prove beneficial for temperature regulation.

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Chapter 8
Assessment of Equipment Using Infrared Thermography in Sports

Minh Phong Luong

Abstract Sporting equipment is increasingly faced with practical problems related to thermal phenomena, irreversible and dissipative processes, inducing aging, damage, degradation, fatigue and failure of the materials and structures under loading service. This text aims to illustrate the use of infrared thermography as a non-destructive, non-contact, real-time and easy to use technique in order to detect, observe and evaluate the evolution of temperature changes caused by the diverse physical processes occurring in sports engineering.

8.1 Introduction

Sports engineering covers various research themes in design and production, materials and sport, biomechanics, instrumentation, modelling, mechanics, motion analysis, dynamics, strength of materials, sports and leisure facilities. In all these areas, thermal aspects should not be ignored because they help identify different product attributes for better competitive sports performance, style, comfort, safety and enjoyment [1]. New technologies have made sports faster and more powerful, and they have also improved the performance, enjoyment, safety and the overall wellbeing of athletes [2]. This leads to an increasing requirement for appropriate testing (1) to ensure product integrity and reliability, (2) to avoid malfunctioning and failure, (3) to aid in better product design, (4) to control manufacturing processes, and (5) to strive for the highest standards in quality and safety.

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8.1.1 Objective

Mechanical engineering deals with various types of materials and structural components. The study of thermal phenomena to identify product attributes follows a well-known process: *thermal phenomena are identified and theoretical models are obtained intuitively from experience*. These must subsequently be *validated*: their predictions concerning the application are compared with relevant experimental results. An approach based on temperature change measurement provides a better understanding of the mechanical behaviour of sporting goods, equipment and accessories. It allows the detection of physical phenomena which can lead to damage, and it leads to new ideas for the improvement of sporting goods and related products. This non-destructive testing technique can effectively evaluate the mechanical performance of sporting goods merchandise in compliance with international standards, or depending upon the requirements of the athletes.

8.1.2 Method

The thermal effects due to thermomechanical coupling in solids have been identified within the general framework of the thermodynamics of irreversible processes based on internal variables. This chapter aims to illustrate the use of infrared thermography as a non-destructive, real-time and noncontact technique to detect, to observe and to evaluate the evolution of temperature changes caused by the diverse processes of irreversible physical phenomena. The results obtained highlight the advantages of differential infrared thermography.

An active thermographic system with external thermal stimulation is scanned from a single side access. When temperature variations occur on the observed surface, the infrared camera records all data for spatial visualization of temperature distribution and temporal separation of the heat images thanks to advanced image processing techniques applied to the thermal response. The thermal data processing consists simply of an image subtraction function between two stages of loading. This technique minimises the thermal noise in real environments and thus facilitates the detection, discrimination and interpretation of the diverse thermal phenomena involved in these non-linear coupled thermomechanical effects. Stress and strain concentrations in loaded materials and structural components occur and result in localized forces that are sufficient to promote plasticity and/or inelasticity. In addition to traditional techniques of mechanical strength evaluation, the technique provides a ready evaluation of (1) a threshold or limit of acceptable damage under service loading beyond which the material will be rapidly destroyed, or (2) fatigue resistance under repeated and cyclic excitations or dynamic solicitations. Finally this approach suggests various potential applications of the thermal scanning technique in diverse sports engineering domains: localisation of dissipative phenomena and rapid evaluation of fatigue limit, non-destructive testing using thermal conduction phenomena and detection of heat sources in sports equipment.

8.2 Principles of Infrared Thermography Testing

Thermomechanical coupling effects have traditionally been neglected in thermal stress analyses. The temperature field and the deformation induced by thermal dilation and mechanical loads were solved separately. However, this effect may become significant when mass inertia is not negligible, due to the flux of heat generated through the boundary of the body, or if the material is loaded beyond its stable reversible limit. The relevance of coupled thermomechanical analysis has been demonstrated for a variety of problems of mechanical engineering, such as fault analysis, damping of stress wave propagation, deformation localisation after bifurcation and strength softening of material due to the heat generated by repeated plastic deformations. Internal energy dissipation has been recognised by a number of well-known scientists [3–5]. Carrying out experiments on the cyclic twisting of cylindrical bars, Dillon [6] identified the work done to the system by plastic deformation as the major contribution to the heat effect, and proposed an internal dissipation rate **Đ** related to the plastic strain rate. The thermal effect due to thermomechanical coupling at the tip of a moving crack has been investigated within the framework of thermodynamics, taking into account stress and strain singularities [7]. The heat generated due to plastic deformation causes a large local temperature increase which is expected to affect the selection of failure modes during dynamic fracture and thus to influence the fracture toughness of the material. Well-developed empirical theories of plastic deformation in metals allowed engineers to predict successfully the behaviour of a variety of structures and machine elements loaded beyond the elastic limit for design purposes. Infrared thermography is a convenient technique for producing heat images from the invisible radiant energy emitted from stationary or moving objects at any distance and without surface contact and without in any way influencing the actual surface temperature of the objects viewed. A consistent theoretical framework is necessary in order to correctly interpret the thermal images. When restricting the analysis to perfectly viscoelastic-plastic material, this leads to the following coupled thermomechanical equation:

$$\rho C_v \theta_{,t} = \rho r + \mathrm{div}(k \text{ grad } \theta) - \left(\beta : D : E^e_{,t}\right)\theta + S : E^I_{,t} \tag{8.1}$$

Equation 8.1. Thermomechanical equation. Where ρ ($\mathrm{kg\ m^{-3}}$) is unit mass; C_v ($\mathrm{J\ kg^{-1}\ K^{-1}}$) = specific heat at constant deformation; C ($\mathrm{J\ m^{-3}\ K^{-1}}$) = ρ C_v the volumetric heat capacity of the material (the energy required to raise the temperature of unit volume by 1 °C or 1 K); r = the heat sources; div ($\mathrm{m^{-3}}$) = the divergence operator; k ($W\ m^{-1}\ K^{-1}$) = thermal conductivity; grad (m^{-1}) = the gradient operator; θ (K) = the absolute temperature; β (K^{-1}) = the coefficient of the thermal expansion matrix; D ($N\ m^{-2}$) = fourth-order elasticity tensor; $E^e{}_{,t}$ (s^{-1}) = the time derivative of the elastic strain tensor; S ($N\ m^{-2}$) = second Piola–Kirchhoff stress tensor; ':' the tensorial contracted product operator; and finally $E^I{}_{,t}$ (s^{-1}) = the time derivative of the irreversible strain tensor

Since the underlying physical processes are highly diversified, the modelling is approached from a purely phenomenological point of view. Such an approach can be useful in the interpretation of the energetics of the thermoelastic-plastic behaviour. The classical theory of rate-independent isotropic or kinematical hardening plasticity is considered to be an adequate basis for such modelling as it offers the simplest constitutive model for elastic behaviour of the material while still allowing consistent inclusion of two-way thermomechanical coupling effects.

When using internal state variables that describe structural changes of material, the right-hand side member will be completed by other terms representing the cross-coupling effects [8]. These effects influence the evolution of temperature through the second-order terms when compared with the internal dissipation term. Their contribution to internal heating during the adiabatic process is small and so they are sometimes neglected.

This coupled thermomechanical equation suggests the potential applications of the infrared scanning technique in diverse engineering domains: detection of heat sources, nondestructive testing using thermal conduction phenomena, elastic stress measurements and localisation of dissipative phenomena. Thus the detected temperature change, resulting from four quite different phenomena, must be correctly discriminated by particular test conditions and/or specific data reduction. This is the main difficulty when interpreting the thermal images obtained from experiments under the usual conditions.

8.2.1 Thermal Phenomena

The first term on the right-hand side of the coupled thermomechanical equation is related to the existence of heat sources or heat sinks in the scanning field. The surface heat patterns displayed on the scanned specimen may result from either external heating, referred to in the literature as passive heating, where local differences in thermal conductivity cause variations on isothermal patterns, or from internally generated heat, referred to as active heating.

8.2.2 Thermal Conduction

The second term on the right-hand side of the coupled thermomechanical equation governs heat transference by thermal conduction, in which the heat passes through the material to make the temperature uniform within the specimen. The second-order tensorial nature of the thermal conductivity K may sometimes be used for the detection of anisotropy of heavily loaded materials. It could also be used to discriminate different thermal phenomena generated by different dissipative mechanisms within the tested object due to their delay in conduction [9].

8.2.3 Thermoelasticity

The third term on the right-hand side of the coupled thermomechanical equation illustrates the thermoelastic coupling effect. Within the elastic range and when subjected to tensile or compressive stresses, a material experiences a reversible conversion between mechanical and thermal energy, causing it to change temperature. Provided adiabatic conditions are maintained, the relationship between the change in the sum of principal stresses and the corresponding temperature change is linear and independent of loading frequency. It is the reversible portion of the mechanical energy generated; this thermoelastic coupling term may be significant in cases of isentropic loading.

8.2.4 Intrinsic Dissipation

The last term on the right-hand side of the coupled thermomechanical equation defines the energy dissipation generated by viscosity and/or plasticity. Internal energy dissipation has been recognised by many scientists, and the work done to the system by plastic deformation has been identified as the major contribution to heat effect. In thermoelastic-plasticity, it is generally accepted that not all mechanical work produced by the plastic deformation can be converted to the thermal energy in the solid. A portion of the work is believed to have been spent in the change of material microscopic structure. The work done, in plastic deformation per unit volume, can be evaluated by integrating the material stress–strain curve. This internal dissipation term constitutes a significant part of the non-linear coupled thermomechanical analysis. The quantification of this intrinsic dissipation for engineering materials is an extremely difficult task without infrared thermography. The infrared thermographic technique is mainly concerned with differences in temperature (or thermal gradients) that exist in a material rather than the absolute value of temperature. The work, reported in this chapter, considers intrinsic dissipation to be the most accurate indicator of damage manifestation. It highlights the advantages of the infrared thermographic technique, used for the detection and discrimination of this non-linear coupled thermomechanical effect within the framework of a consistent theoretical background. Several applications have been proposed for materials testing in sports equipment [10–12].

8.3 Infrared Thermography Applications to Sporting Equipment

Diverse and various applications of the infrared thermography technique to sporting equipment are based on each or in conjunction with several terms of the right-hand side of the above coupled thermomechanical equation.

8.3.1 Infrared Thermography Screening of Heat Rise in Racing Cars

Thermal imaging has been used by tire makers for product development, both for racing and passenger cars. The air pressure inside the tires supports the weight of the vehicle. Since air is a gas, it expands when heated and contracts when cooled.

According to the classical gas law Pv = rT—where P ($\mathrm{N\ m^{-2}}$) is the pressure; v ($\mathrm{m^{-3}}$) is the volume; r (=287 $\mathrm{J\ kg^{-1}\ K^{-1}}$) is the gas constant and T (K) is the temperature—temperature measurement is related to tire pressure that has to be checked to assure that the influences of time, changes in ambient temperature or a small tread puncture have not caused it to change. The tire pressure recommended in the tire information list is the vehicle's recommended cold tire inflation pressure. Some racing teams at all levels of the Formula One racing use thermal cameras to control the tires to make sure they are always running adequate tires with the right air pressure for the conditions so they have just the right contact patch.

Racing tires are substantially different from those on a passenger car:

- Race car tires are much wider—up to 12 in (30.48 cm) wide in the front and 16 in (40.64 cm) wide in the rear, whereas the typical passenger car tire is 7–9 in (17.78–22.86 cm) wide.
- Racing tires may be completely smooth to maximize the amount of rubber touching the track surface.
- The rubber on the face of the tires is extremely soft. It is more like a soft rubber eraser than anything else, and very unlike the hard rubber found in passenger car tires.

In addition, racing tires get very hot due to tread flex and friction generated by rotational speed and by cornering and braking. The higher the load and the higher the speed, the hotter the tire will get. The heat though, will not be evenly distributed. One tire may run hotter than the others, or one area of the contact patch may be hotter than another. If the technician can accurately measure tire temperatures and observe how those readings are distributed across the tire, he can adjust tire pressures and suspension to achieve improved performance.

To determine the temperature of racing car tires, it is vital that the driver uses the most robust and reliable thermometers on the market. Infrared thermometers run on thermal, or infrared energy, which is light with a long wavelength that makes it invisible to the human eye. It is the part of the electromagnetic spectrum that is perceived as heat. Unlike visible light, in the infrared world, everything with a temperature above absolute zero emits heat, even very cold objects like ice. The higher the object's temperature, the greater the IR radiation emitted. Infrared thermography allows us to see what our eyes cannot.

When taking race tire temperatures, it is important to keep the tires as close to operating temperature as possible. Therefore, the pilot must run two to three hot laps to heat the tires and get into the pits quickly. Temperature readings are taken as soon as possible, since the tread surface cools rapidly.

Maintaining sufficient air pressure is required if the tires are to provide all of the handling, traction and durability of which they are capable, but excessive pressures lead to irregular wear. "Cupping", or too much wear in the center of the tread, is a sign of overpressure. Too much wear to the shoulders of the tire is a sign of too little pressure. Combined with cold-stiffened rubber, the loss of pressure can sometimes cause tires to spring otherwise unexplainable leaks. Low pressure may progressively damage the tire, particularly the sidewall of the tire as it starts to fold over. Air pressure maintenance is actually one of the most important repeating maintenance items on the car. Proper air pressure maintenance leads to better gas mileage, avoids irregular wear and extends the life of the tires by thousands of kilometres. Due to the importance of tire pressure has on vehicle safety and efficiency, a tire-pressure monitoring system (TPM) is becoming increasingly adopted for passenger vehicles. It is an electronic system designed to monitor the air pressure inside the pneumatic tires on various types of vehicles. It warns the driver that at least one or more tires are significantly under-inflated, possibly creating unsafe driving conditions.

Because of their versatility, infrared thermometers are also used to detect sources of heat that affect the driver, locate dead engine cylinders, or read the temperature of bearings, brakes or the track.

In race cars, non-contact temperature measurement is useful for screening heat sources generated by brakes/sealed wheel bearings, engine components, exhaust systems, tires, cooling systems, compact heat exchangers [13] and particularly engine overheating. Most engines are designed to operate within a temperature range of about 90–105 °C. A relatively constant operating temperature is essential for proper emissions control, good fuel economy and performance. But problems can arise that cause the engine to run hotter than normal, resulting in engine overheating.

8.3.2 Quality Screening of Clay Tennis Court After Wetting

The conduction term of the thermomechanical equation governs the heat transfer by the thermal conduction and radiation at the surface in which the heat passes through the material leading to a uniform structure temperature. The second-order tensorial nature of the thermal conductivity k may be used for the detection of anisotropy in heavily loaded materials.

Variations in thermal conductivity may arise because of local inhomogeneities or flaws in the material. When an unsteady state exists, the thermal behaviour is governed not only by its thermal conductivity but also by its heat capacity. The ratio of these two properties is termed the thermal diffusivity $\alpha = k/C$ ($m^2\ s^{-1}$), which becomes the governing parameter in such a state. A high value of the thermal diffusivity implies a capability for rapid and considerable changes in temperature. It is important to bear in mind that two materials may have very dissimilar thermal conductivities but, at the same time, they may have very similar diffusivities.

The French Tennis Open uses clay courts, which are generally more common in Continental Europe. Although less costly to construct than other types of tennis courts, their maintenance costs are high as the surface must be rolled to preserve flatness. No court surface varies in the height of the ball's bounce as much as clay court. On cold, wet clay, the ball bounces quite low; on dry, hot clay, it bounces quite high.

Clay courts are considered "slow", because the balls bounce relatively high and more slowly, making it more difficult for a player to deliver an unreturnable shot. Clay courts heavily favour baseliners who are consistent and have a strong defensive game, which allow players such as Rafael Nadal, Björn Borg, Chris Evert, and Justine Henin to be successful at the French Open. Clay court players use topspin to trouble their opponents. Movement on gravel courts is very different from movement on any other surface. Playing on clay often involves the ability to slide into the ball during the stroke, as opposed to running and stopping like on a hard or grass court. Clay courts are unique in that the ball bounce leaves an impression in the ground, which can help determine whether a shot was in or out. The properties of the surface influence the style of play and affect the quality of performance.

Critics of red clay courts point to the constant need to wet them down, with problems of renewing the surface if it dries out. The water content is a key characteristics and it must be balanced. The temperature of a bare wet soil surface could be measured with a narrow bandpass infrared radiation thermometer [14]. In this case, infrared thermography readily provides a rapid control of the uniformity of the temperature of the playing surface that is related to the mechanical resistance of the clay court surface.

8.3.3 Thermoelastic Coupling in Sport Equipment Testing

Experience shows thermoelasticity to be a common type of behaviour. It is characterized by *reversibility* of the material response to the excitation it undergoes. Thermoelastic behaviour is modelled by assuming that current values of the temperature and strain tensor in the material element are sufficient to define its physical state. The free energy arises as the *thermodynamic potential*, a function of the current values of the temperature and strain tensor. The stress tensor is obtained by differentiating with respect to the strain tensor. In an isotropic material undergoing small perturbations, linear thermoelasticity is characterized by *two* elastic constants and *one* thermal expansion coefficient. Elastic and thermal strains can be uncoupled as follows: total strain = elastic strain + thermal strain. In practice, the thermoelastic equilibrium problem is solved by using the superposition principle. The problem consists of adding together the solutions: (a) of the isothermal problem with excitations and (b) of the purely thermal problem.

Check-experiment of energy restitution on soccer ball

High-level matches deserve a soccer ball that respond with accuracy and a soft touch. In the past, many soccer balls made by different manufactures varied in quality when used in matches. Now soccer balls with the organization's official approval logo imprinted on them, adhere to a higher standard of quality and are more consistent in how they perform during matches. Testing procedures for the balls submitted for these designations are designed to simulate match conditions: (1) *Circumference test* for a well-balance response in play; (2) *Sphericity test* which ensures the ball's in-flight stability; (3) *Rebound test* to make sure that the ball bounces in a predictable manner; (4) *Water absorption test* which ensures a limited increase in weight; (5) *Weight test* which ensures a consistent playing response when the ball is struck; (6) *Loss of Pressure test* in order to remain playable; and finally (7) *Shape and Size Retention test* which ensures that the footballs last, even in the most challenging situations for a better playing performance. Manufacturers have to submit seven balls if they are applying for "FIFA Inspected" status, and ten samples if they seek the "FIFA Approved" label.

The manufacturer of the 1998 World Cup soccer ball (Fig. 8.1a) claimed that the Tricolore soccer ball is faster and more accurate than any other soccer ball. It contains hollow acryl-nitryl micro beads of 70 μm in diameter, pressurised at 14 MPa. They are then highly compressible and capable to restitute a great amount of the kicking energy.

Figure 8.1b depicts a check-experiment on the soccer ball kicked by a steel ball. The elasticity of the collision between soccer ball and steel ball is given by a measure of how much bounce there is, or in other words, how much of the kinetic energy of the colliding objects before the collision remains as kinetic energy of the objects after the collision. With an inelastic collision, some kinetic energy is transformed into deformation of the material, heat, sound, and other forms of energy, and is therefore unavailable as motion. A perfectly elastic collision has a

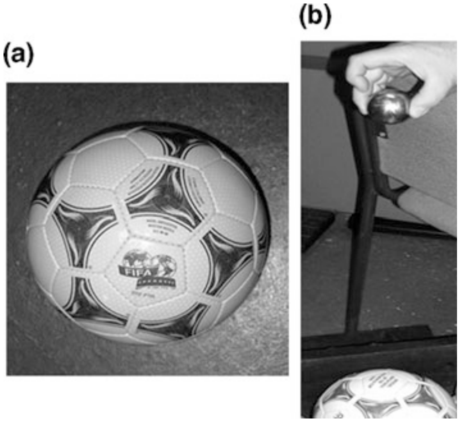


Fig. 8.1 **a** The Tricolore soccer ball used underglass print technology with a thin layer of syntactic foam. **b** Check experiment of energy restitution on a soccer ball

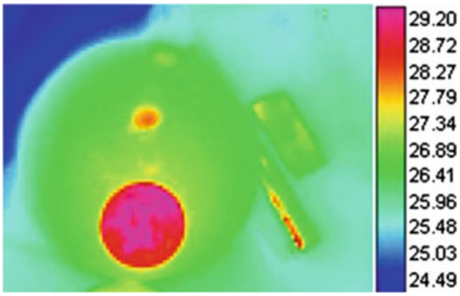


Fig. 8.2 The kicked soccer ball is the large circle at 26.5 °C. The steel ball striker is the medium size circle at 30 °C. A very localized hot zone at nearly 28 °C is due to the increased pressure in the pressurised micro beads (temperature scale is given in degrees Celsius)

coefficient of restitution of 1 (ratio of the differences in velocities before and after the collision). A thermal image (Fig. 8.2) shows the kicked soccer ball (green circle), the steel ball striker (red circle) and an extremely localised hot zone (small red zone) due to increased pressure in the pressurised micro beads. The pressurised micro beads store elastically the kicking energy according to the equation $p\,v = R\,T$ and $h = c_p\,T$. In case of perfect gas with gas constant R and heat capacity c_p, the variables are pressure p, specific volume v, temperature T and specific enthalpy h.

The experiment evidenced:

- a very localised heat change decreasing rapidly (Fig. 8.3),
- several consecutive experiments at the same location confirm that the heat increase remains very localised and no accumulation of temperature changes occurs on the soccer ball. This fact demonstrates that dissipative behaviour is negligible.

A fast soccer ball kick has been recorded 129 km/h (80.1 mph) in Madrid, Spain on 29 October 2001. It was achieved by Francisco Javier Galan Màrin at the studios of *El Show de los Récords*. However, according to the Guinness Book of Records

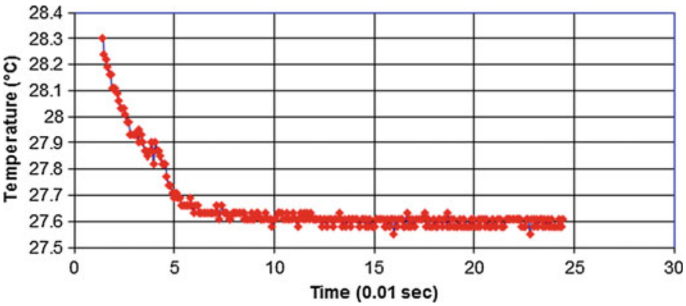


Fig. 8.3 Evolution of temperature versus time during impact

Ronny Heberson shook the goal with an incredible 132 mph for Sporting Lisbon against Naval in 2006. The ball travels so fast that it becomes almost imposible to see during the flight of the ball towards the goal. Top professional players are exploiting the chaotic flight and speed of modern balls used in today's matches. A change of external structure called the PSC structure (Power, Swerve and Control) can give outfield players the advantage. Goosebump-like shapes on the surface layer give the ball more power and swerve.

In addition when the soccer ball offers a high coefficient of restitution with negligible deformation, the soccer player can precisely kick it slightly off center, causing it to rotate around a given axis. When the ball travels, air moves over the ball according to the location of kicking impact and generates the Magnus effect. Different spins can cause different effects on the ball generating different flight paths of the ball. With a backspin on a ball, the air will go faster over the ball with more pressure underneath. This will cause the ball to rise and travel farther.

Design testing of a light sport airplane

Ultralight aviation is the flying of lightweight, 1 or 2 seater fixed-wing aircraft. The integrity of any novel or unusual design feature having an important bearing on safety should be established by test. Design values of strength must be chosen so that no structural part is under strength as a result of material variations or load concentration, or both.

Strength requirements are specified in terms of limit loads (the maximum loads to be expected in service) and ultimate loads (limit loads multiplied by prescribed factors of safety). The light sport aircraft wings must be tested to ensure great handling, strength under load, and flight performance across a range of airspeeds and angles of attack.

Within the linear elastic range and when subjected to tensile or compressive stresses, a material experiences a reversible conversion between mechanical and thermal energy causing temperature change. Provided adiabatic conditions are maintained, the relationship between the change in the sum of principal stresses and the corresponding change in temperature is linear and independent of loading frequency [15].

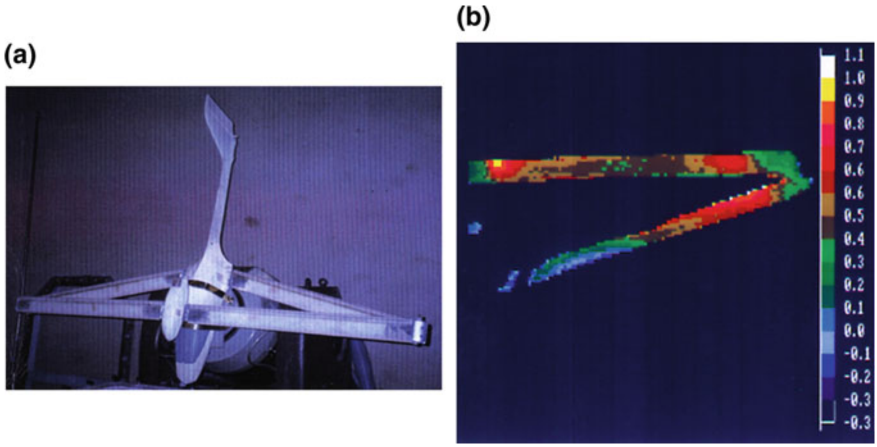


Fig. 8.4 **a** Reduced scale model of a double-winged aircraft subjected to vibratory loadings. **b** Elastic stress concentrations recorded on the test specimen during vibratory loading (temperature scale is given in degrees Celsius)

A vibratory test was performed on a reduced scale model of a double-winged aircraft (Fig. 8.4a) in order to evaluate the weakness zones around connections (i) between the two wings themselves, and (ii) between the wings and the fuselage. The double-wing design is assumed to lead to greater maneuverability. The big disadvantage of the biplane layout was that the two wings interfered with each-other aerodynamically, each reducing the lift produced by the other. This interference meant that for a given wing area the biplane produced more drag and less lift than a monoplane. This mechanical statement is supported by the hot locations on the wings caused by stress concentrations (Fig. 8.4b). High local stresses can cause objects to fail more quickly. These experimental results are used to assist in a better design of the light sport airplane prototype, minimizing stress concentrations and if posible avoiding them.

8.3.4 *Damage Occurrence and Detection in Sports Materials*

In materials testing in an industrial environment, thermal noise often generated by gripping systems may sometimes obscure the intrinsic dissipation of the tested specimen. This difficulty can be overcome when using thermal image subtraction or differential thermography.

Mechanical performance of tennis strings under tension

Natural gut has been regarded as the premiere tennis string since the early 1800s. It has been, and remains, the most frequently used string on the pro tour. It has better tension retention than any other material, and also is softer than any other material used for tennis strings. It provides the most energy return, meaning it is the most efficient string. It remains soft at high tensions while other materials tend to stiffen dramatically. This allows gut string to enable players to string rather tightly to improve ball control without losing much rebound efficiency (power) and without greatly increasing impact shock, which can hurt the elbow and other joints.

Damage and failure behaviour of natural gut strings and others types of synthetic tennis racket strings are an important consideration for skilled tennis players who should be highly aware of their equipment's performance relative to their personal needs and game style. Much engineering research has been conducted to determine optimal string tension (Fig. 8.5) for different size rackets made from various types of materials [16]. The effect of varying string tensions is important to skilled players wanting to improve their shot velocity and control [17]. When string is loaded, it deforms as a whole in spite of its heterogeneous characteristics and its localised defects. Stress concentrations occur and result in localised forces that are sufficient to promote plasticity and inelasticity. Failure mechanisms of string specimens subject to tensile loading are readily evidenced by infrared thermography. Gut is a natural animal fibre, manufactured from the smooth muscle portion of sheep or beef intestines through a sophisticated chemical process of washing, bleaching, twisting, drying, and refining to ensure strength and uniformity [18]. This product is designed for an optimisation of playability, comfort, hitting power and durability.

The intrinsic dissipation, generated by plasticity, is considered as a highly sensitive and accurate indicator of damage manifestation. Thanks to the thermo-mechanical coupling [19], infrared thermography is used to observe the physical

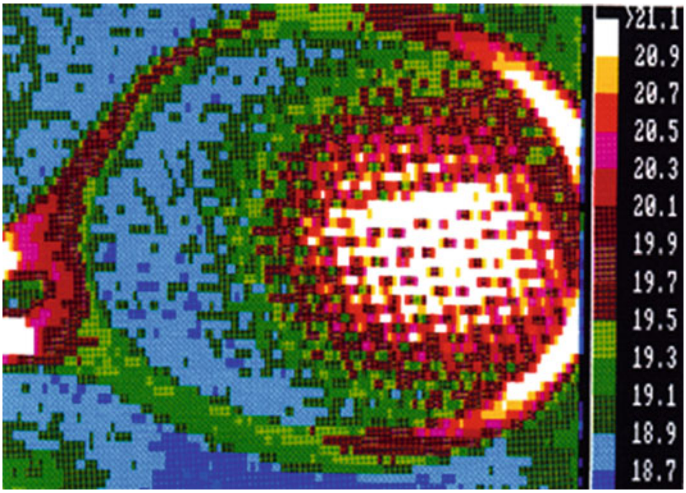


Fig. 8.5 Infrared thermography of a tennis raquet impacting the ball (temperature scale is given in degrees Celsius)

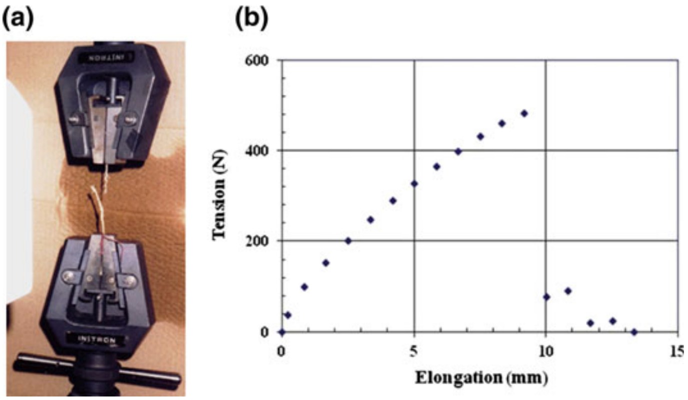


Fig. 8.6 **a** Specimen of a natural gut string subjected to tension loading. **b** Experimental elongation versus tension curve of a natural gut string specimen

processes of damage and to detect the onset and the evolution of damage and failure processes of tennis string when the specimen is subjected to increasing tensile loading (Fig. 8.6).

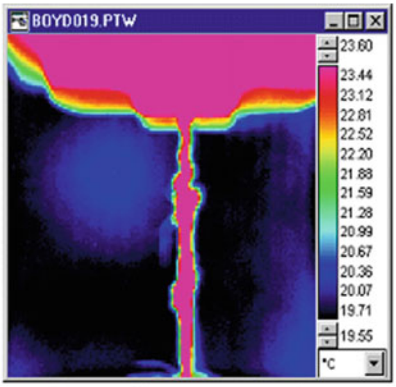
If the evolutions of damage and intrinsic dissipation are assumed identical, a thermal image processing give the intrinsic dissipation at tension T as shown in Fig. 8.7. It readily gives a measure of the material damage and locates the failure of the gut string specimen. In addition it permits a graphical evaluation of the limit of acceptable damage **LAD** that separates low and high regimes of dissipation or damage manifestation (Fig. 8.8). This tension—dissipation plot precisely defines a threshold under which natural gut provides its best mechanical performances.

Material composites have increased the diversity of design and manufacturing for sports products. There are a large variety of synthetic products including nylon, artificial gut, graphite string, oil-filled string, etc. Very specific designs are targeted to match the physical capability of each player. Can their mechanical performance be characterised in term of damage and durability? In the interaction of the ball and the strings, the kinetic energy of the ball is converted into potential energy stored in both ball and string deformation. By storing a larger fraction of the incoming energy in the strings, less is dissipated, and more is returned to the ball's rebounding kinetic energy [17]. The shock vibrations of the wrist joint are transmitted from the racket with an impulse at the impact location and several vibration mode components of the racket frame and strings [20]. The higher the string tensions the higher the vibration frequency. This fact influences the feel or comfort of the arm or hand on impact.

Dry sliding of natural gut string at nodes

In order to produce ball spin in tennis, the player must accelerate the racket head through impact to brush the backside of the ball: (a) upward for topspin, (b) downward for underspin and (c) sideways for sidespin. The resulting effect is to

Fig. 8.7 Evaluation of intrinsic dissipation of a natural gut specimen under tension by subtraction between two thermal images (temperature scale is given in degrees Celsius)



Thermal image at tension T

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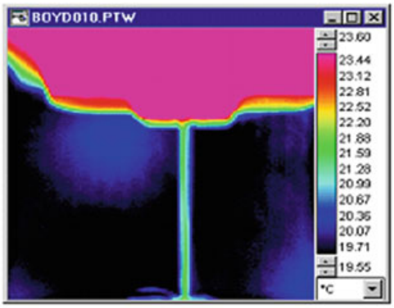

Thermal image at tension T = 0

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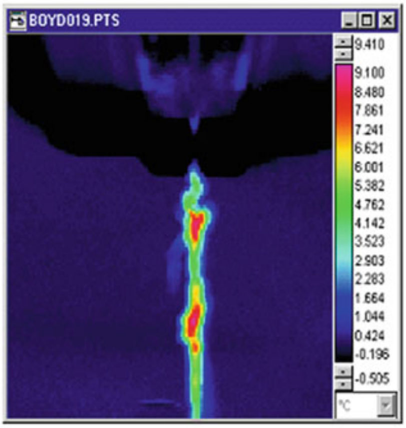
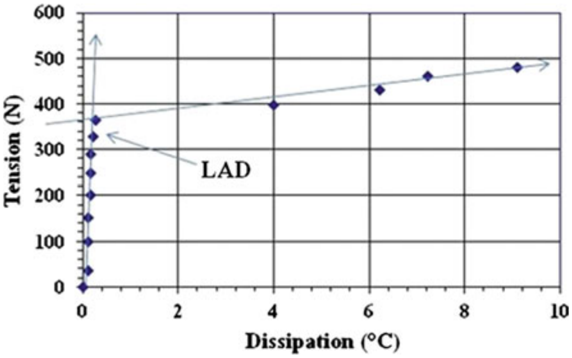


Intrinsic dissipation subject to tension T

Fig. 8.8 Graphical determination of the limit of acceptable damage **LAD** of a natural gut string in tension



curl the tennis ball trajectory. When the tennis ball travels, air moves over the ball. The air will move more quickly around one side, making less pressure on that side of the ball (faster speed of air corresponds to lower pressure). On the other side of the ball, the air moves more slowly, as the spin is going directly against the flow of the air, causing there to be more pressure on that side of the ball. The ball is pushed in the direction from high pressure to low pressure, making the ball curve. Rafael Nadal uses a forehand grip which places the palm of the hand underneath the racket handle. His forehand allows the ball to clear the net with a high net clearance as he uses an upwards swing; as a result more topspin is produced.

The more vertical (or horizontal) the racket swings (in either direction), the more ball spin will be produced. The amount of spin a player imparts on the ball, combined with a high stroke velocity, generates dry sliding between longitudinal and transverse strings at nodes located in the racket's effective hitting zone. Relative movements between longitudinal and transverse strings occur depending on the type of ball-racket impact. They lead to tribological phenomena, such as friction, wear, pitting and fretting fatigue.

Fretting is a major problem in optimising tennis strings. It is defined as the surface damage induced by small-amplitude oscillatory displacements between strings in contact. This damage can either be wear or crack nucleation, depending on the prescribed forces or the displacement amplitude.

Considering a contact problem, in which a moving longitudinal string (9 cm long) is in contact with a fixed transverse string (5 cm long). The two strings were initially stretched at 200 N. An electromagnetic vibrator at a frequency of 1 Hz controls the cyclic motion of the longitudinal string. Force sensors respectively measure the normal and tangential contact forces during testing (Fig. 8.9a). Infrared thermography has been used to estimate tribological parameters, such as a frictional temperature rise (Fig. 8.9b), the shape and the size of the contact area (Fig. 8.9c).

Infrared thermography readily detects heat dissipation by Coulomb friction at contact location where sliding occurs between longitudinal and transverse gut strings. The experimental data demonstrate that wear phenomena occurring in tennis rackets could become significant in long matches such as the men's final of 1988 US open Tennis Tournament Lendl versus Wilander (4 h, 54 min with several

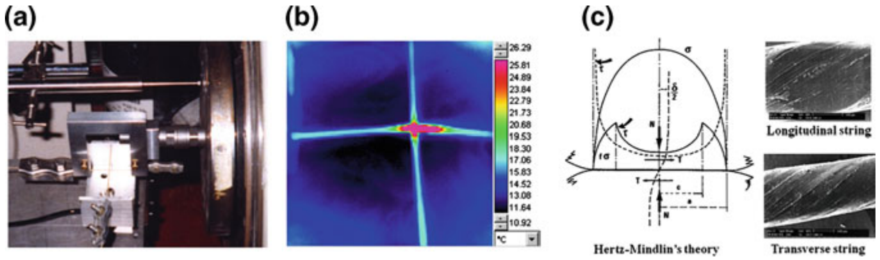
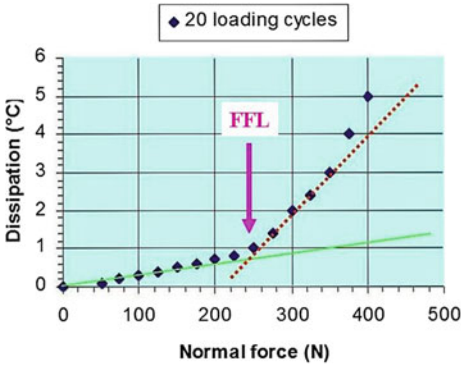


Fig. 8.9 **a** Experimental set-up for fretting fatigue testing on natural gut string at nodes. **b** Thermal image of natural gut string at nodes during fretting fatigue testing (temperature scale is given in degrees Celsius). **c** Contact between the 2 perpendicular gut strings

Fig. 8.10 Experimental determination of fretting fatigue limit (**FFL**) of a natural gut string using infrared thermography



thousands of strokes) or the men's 1st round of Wimbledon 2010 Isner versus Mahut during more than 11 h. The main parameters identified are string tension, racket stiffness, effects of spin, hitting power, etc.

These results have demonstrated that the dissipativity of tennis string material under tension or frictional loading is highly sensitive and an accurate predictor of damage. Owing to the thermomechanical coupling, infrared thermography offers the possibility of a non-destructive, non-contact testing of string degradation and damage. It provides a ready determination of a fretting fatigue limit **FFL** (Fig. 8.10), beyond which the string will fail in a long match. The opportunities offered by thermal techniques with remote operation and fast surface-scanning rates are particularly attractive for sports equipment.

8.3.5 Safety Control of Playing Surfaces

Each sport requires an individual approach to the design, installation and maintenance elements in the development of successful sport surfaces. Sports managers are often charged with providing cost effective, safe playing surfaces for athletes. The challenge is to create a uniformly dense cover (using soil, turf or synthetic materials) that provides sure footing and one that is able to tolerate and recover from the extreme wear and tear to which high-use fields are subject.

Common injuries could result from:

(a) *Heat*. Grass dissipates heat and naturally cools the environment. Heat related injuries are rare. Synthetic field can reach extremely high temperatures even at head height.
(b) *Abrasions, burns, grazes*. Natural turfgrass field is generally soft and not abrasive. Problems only arise when the ground has become bare and dry. Most synthetic fibers are relatively non-abrasive. The choice of infill is critical. Sand is more abrasive and rubber can cause friction burns if sliding.
(c) *Traction: knee and ankle sprains and muscle strains*. The choice of grass type is important for traction. Too much traction has been linked to an increased risk of severe knee injuries and too little traction to muscle strains and facial fractures. On synthetic field, footwear plays a major role in the amount of traction a player experiences.

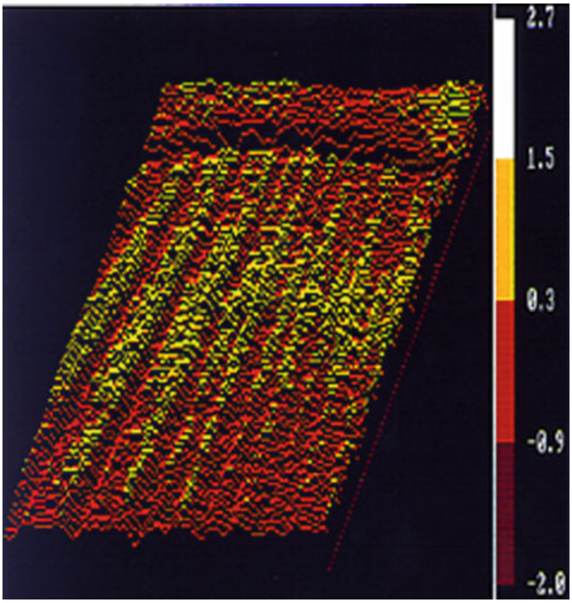
In order to reduce the injury risk of skin burning and skin abrasion in cases of player-to-surface interaction, safe control of different playing surfaces should be done and communicated to users. A slip/skid resistance tester was used in conjunction with an infrared camera. The process is quite simple. The pendulum is released from the horizontal position by a quick release button. It swings down with uniform force each time, and the rubber slider—that simulates natural skin—at the bottom of the pendulum contacts the playing surface for a fixed length previously set by highering or lowering the height of the pivot of the pendulum (French Standard NF EN 1339). The rise of temperature detected by the infrared camera will be dependent on the friction/resistance the rubber meets on the playing surface (Fig. 8.11).

If the playing surface is abrasive, it can lead to friction burns when a player slides on the surface. However a certain amount of friction is necessary to slow the player down as he slides.

Mechanical properties of wood used as green building materials

Sport is great driver of materials technology for the designers of sports and leisure facilities using glulam timber beams, laminated timber, laminated veneer lumber (LVL), plywood, particleboard, fibreboard, thermowood. Sports structures such as multi-sport wooden halls are a particularly suitable application for wide-span glulam roofs. This is supported by the light weight of the material, combined with the ability to furnish long lengths and large cross-sections. Wooden halls are often lighter and more competitive than comparable constructions with alternative building materials. Combination of high quality wood, covered with membranes system offers great value, high durability and comfort.

Fig. 8.11 Heat rise after skid resistance testing on a synthetic playing surface (temperature changes are given in degrees Celsius)



Wood is a natural product of biological origin [21, 22]. It is a very variable and heterogeneous material. Its mechanical properties are affected by the presence of knots, checks, shakes, splits, slope of grain, reaction wood and decay, etc., and anisotropy. Stress concentrations occur because the knot interrupts wood fibres. Checks, shake and splits all constitute separations of wood fibres. Slope of grain has a marked effect on the structural capacity of a wood member. Reaction wood or abnormal wood is hard and brittle, and its presence denotes an unbalanced structure in the wood. Decay is a disintegration of the wood, caused by the action of fungi. A connector or fastener is a mechanical device (nails, bolts, screws, etc.) or mechanical assembly (bolted shear plates, nailed metal truss plates, etc.). A glue or an adhesive is used to hold together two or more pieces of wood or wood based products. It is generally very difficult to quantitatively evaluate damage in these cases.

When a wood or a structural wood product is loaded, it deforms as a whole in spite of its heterogeneous characteristics and its localised defects. Stress concentrations occur and result in localised forces that are sufficient to promote plasticity. At the macroscopic level, breakdown is accompanied by both loss in stiffness and accumulation of irrecoverable deformation. At the structural level, breakdown appears as micro cracking and possibly slippage at component interfaces. Damage and failure may thus be viewed as a micro structural process through the activation and growth of one pre-existing flaws or of a site of weakness, or through the coalescence of a system of interacting small defects and growing micro cracks. Macroscopically it occurs a localisation of intrinsic dissipation before a visible failure. The stress level, corresponding to the activation of the defects, is related to the defect size and connected with the encompassing micro structure.

Non destructive and non contact tests are thus needed to define wood and wooden product properties (1) to establish strength, (2) to optimise design values and (3) to insure quality control.

Infrared thermographic scanning of pine wood specimens

Pine wood is an orthotropic material; that is, it has unique and independent mechanical properties in the directions of the three mutually perpendicular axes: the longitudinal axis **L** parallel to the fibre (vertical grain), the radial axis **R** normal to the growth rings and perpendicular to the grain in the radial direction, and the tangential axis **T** perpendicular to the grain but tangent to the growth rings [23].

Three series of monotonic unconfined compression tests have been conducted on square specimens of pine wood, prepared along its three anisotropy directions. The wood specimens were especially designed with enlarged ends to prevent from sliding, bending or premature buckling, caused by heterogeneity, bad alignment of compression loading, or others significant end effects. Infrared thermography readily depicts intrinsic dissipation localisation announcing quite different mechanisms of damage preceding wood failure, according to the three directions of wood anisotropy (Fig. 8.12). The longitudinal L-specimen fails by local crushing of the fibres at ends leading subsequently to a vertical splitting (Fig. 8.13a). In the R-specimen, crushing of the hollow wood fibres in the spring or early wood regions of some growth rings can often be seen (Fig. 8.13b). The T-specimen fails in an unsymmetrical mode because of the finite growth ring diameter (Fig. 8.13c).

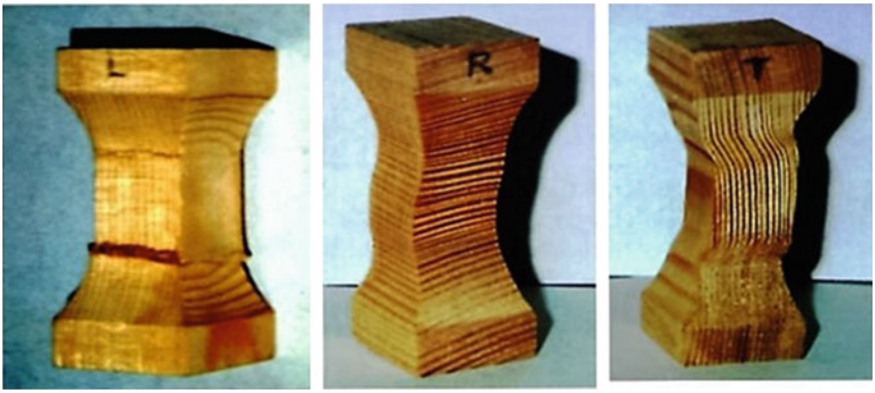


Fig. 8.12 Failure modes according to the anisotropy directions (longitudinal L, radial R and transverse T)

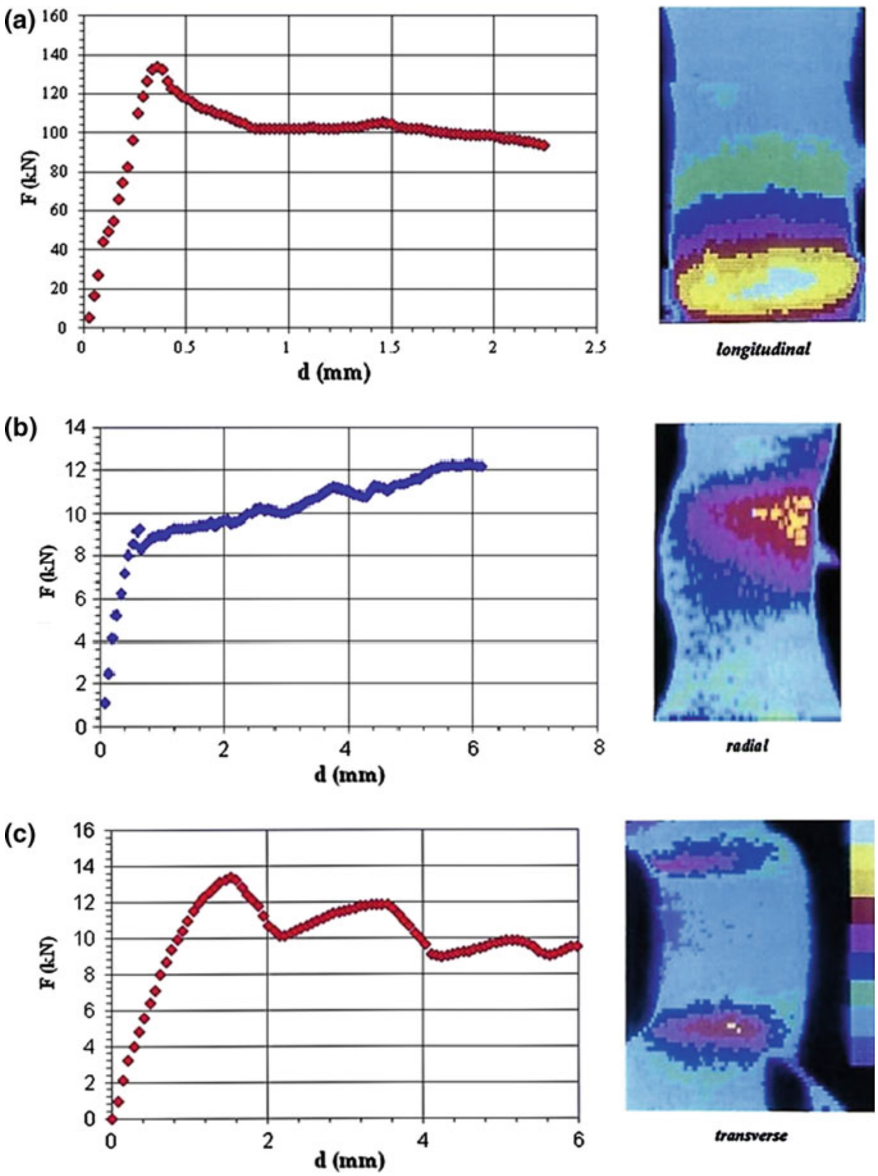


Fig. 8.13 **a** Mechanical behaviour of a clear L-specimen parallel to the grain. **b** Mechanical behaviour of a clear R-specimen perpendicular to the growth rings. **c** Mechanical behaviour of a clear T-specimen perpendicular to the grain and tangent to the growth rings

Infrared thermographic scanning of metal-plate-connected wood-splice joints

One prime advantage of wood as a structural material is the ease with which wood structural parts can be joined together with a variety of fastenings: nails, spikes, screws, volts, lag screw, drift pins, staples, and metal connectors of various types.

Metal-plate-connected wood trusses are widely used in residential construction and continue to be increasingly used in agricultural and other commercial construction. A reason for the widespread use and continued growth of applications for wood trusses concerns the efficiency and effectiveness of punched-metal-plate connectors. Current design procedures [24] are based upon simplified assumptions of connection behaviour and have proven to be quite adequate for truss applications in light-frame redundant assemblies. The increased use of metal plate connected trusses, in applications involving longer spans with fewer redundancies, suggests that a more thorough understanding of the behaviour of metal plate connections would be beneficial for upgrading design procedures [25].

As infrared thermographic scanning offers new information on metal plate connection behaviour, refinement of design procedures can be made as needed and new, more effective, and specialised truss-plate configurations can be contemplated. Although the actual configuration of metal connector plates varies widely among manufacturers, the plates generally consist of galvanised sheet steel of 14–20 gage with teeth of 1/4–3/4 in. (6.4–19.0 mm) punched in a regular pattern across the plate. The long side of the punched rectangular holes defines the major axis of the plate. The plates are pressed into the wood members on each side of a joint, and the teeth act as nails in transferring load from the wood member into the steel plate and into the adjacent wood member. In a truss, this connection system involves a complicated transfer of load as the metal teeth interact with wood at various grain orientations and in various loading situations. Metal plate connections exhibit a non-linear, semirigid load deformation response. Failure modes include the teeth pulling out of the wood, failure of the wood member within the plated region, yielding of the plate in tension (Fig. 8.14) or shear (Fig. 8.15), and compression buckling of the plate in gaps between wood members.

With growing concerns over climate change and the pressure to reduce the carbon footprint of the built environment, building designers are increasingly being called upon to balance functionality and cost objectives with reduced environmental impact. Wood has many attributes that make it obvious choice in green building, in particular it has come from a sustainably managed resource. It grows naturally, using energy from the sun, and is the only major building material that is renewable, re-usable and sustainable. When considered over its life cycle, wood outperforms both steel and concrete in terms of embodied energy, air and water pollution, and others environmental impacts. It contributes to a building’s energy efficiency and indoor air quality, and has an important role to play in the fight against climate change. The emergence of mass timber products such cross laminated timber (CLT) is allowing designers to create a broader range of low-impact sports and leisures structures.

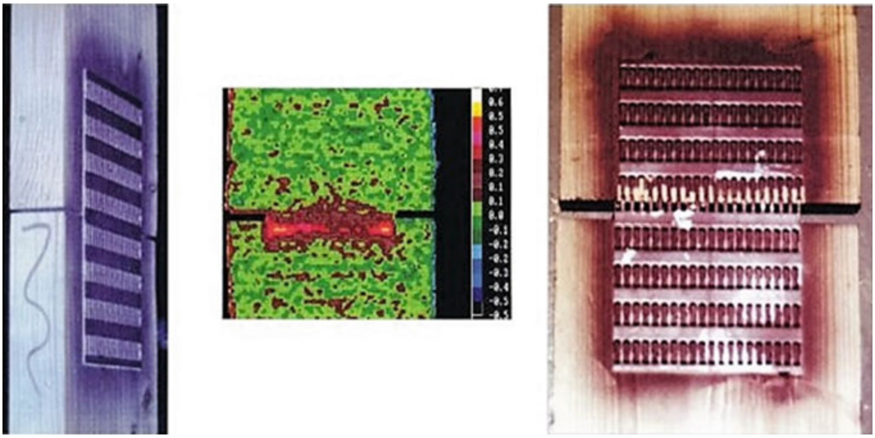
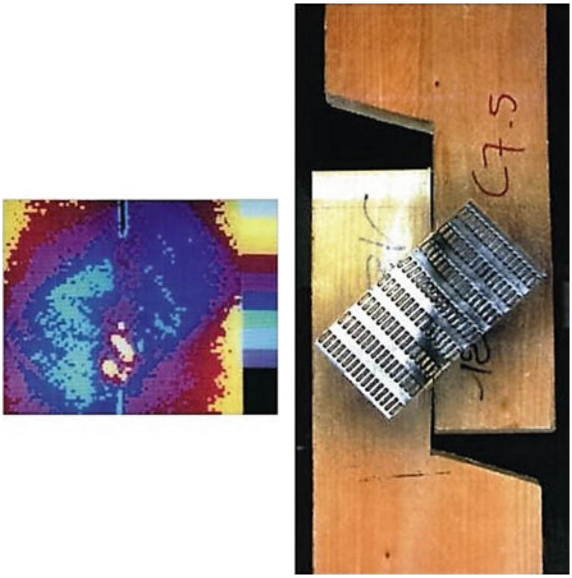


Fig. 8.14 Infrared scanning of splice joint under tension loadings (temperature changes are given in degrees Celsius)

Fig. 8.15 Infrared scanning of splice joint under shear loadings (temperature changes are given in 0.2 °C for each colour)



8.4 Conclusions

This chapter has shown that:

(a) The infrared thermography technique offers a versatile temperature tool that adapt to the most demanding needs for smart race car teams.
(b) It could be used to control the quality of clay tennis court after wetting.

(c) The thermoelastic behaviour of material optimises the design of sport prototype and
(d) The dissipativity of engineering materials or structures of sport equipment under solicitations is a highly sensitive and accurate predictor of health impacts and damage of construction materials involved in green building of leisure and sports facilities.

Thanks to the thermomechanical coupling, infrared thermography provides a non-destructive, non-contact and real-time test to observe the various phenomena generating temperature changes and the physical process of degradation based on the occurrence of its intrinsic dissipation. It thus readily provides a measure of the material damage and allows definition of a limit of acceptable damage and fatigue limit under load beyond which the material is susceptible to failure. It should be pointed out that the inelastic strain due to compressive loading provides information only on the current geometry while the internal state variables provide information on the internal state and on the micro-structural defects.

The method allows not only qualitative studies such as finding flaws, defects or weakness zones, but also quantitative analysis of the effects of flaws and defects on strength and durability of structural components. Several published results demonstrate the versatility of infrared thermography technique in various domains of application, provided that the physical phenomena are correctly interpreted in a consistent theoretical framework.

The main interest of this energy approach is to unify microscopic and macroscopic test data. The parameter intrinsic dissipation under consideration is a scalar quantity, easy to evaluate accurately. Subsequently it may suggest multiaxial design criteria, highly relevant for full scale testing on sport equipment.

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Chapter 9
Infrared Thermography: A Possible Role in Psychophysiology of Sport?

Damiano Formenti and Arcangelo Merla

Abstract Infrared thermography (IRT) is an upcoming, promising methodology in the field of psychophysiology. Mental and emotional components of behavior play an important role in the determination of human performance in sporting competition scenario. Driven by sympathetic nerves activity, affective and emotional states derive from muscular activity, skin blood flow and perspiration patterns in specific body parts. The goal of this chapter is to introduce assessment of emotional states and computational psychophysiology through thermal infrared imaging in sport and exercise.

9.1 Introduction: The Importance of Psychophysiology in Sport and Exercise

In today's highly competitive world of sport events, athletes and sportsmen of various levels are looking for ways to get bigger, stronger, and faster, with the aim to excel in competitions. Technological advances in equipment also play an important role in rising performance. However, physical and physiological components of the performance represents only a few of the factors necessary for rising success in sport competitions. In fact, it is well accepted in the literature that psychological side of sport (i.e., motivation, concentration, mental toughness) is also critical to success [1, 2]. As regard, several important athletes of various

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disciplines regularly acknowledge the importance of the psychology of sport and the need to work on their mental capacities. The last decades have been characterized by an increase in the involvement of sport psychologists by both individual athletes and professional teams and federations. This thanks to the fact that growing attention has been devoted to the study of the interaction between the brain and the body in the field of sport and exercise [2].

The relationship between brain and body has always been a subject of interest in research. The science aimed to study such brain-body relationship is denoted as psychophysiology. Psychophysiology has been defined by Sternbach [3] as the inference of psychological and emotional states from an examination of physiological measures. According to this definition, the electrical signals derived from physiological measures are recorded from the body surface of subjects under investigation [3].

Looking at the development of psychophysiology back in the history, it seems that the main idea of psychophysiology has been that every physiological modification is accompanied by a parallel change reflected in the mental and/or emotional state [4]. Specifically, authors formulated this psychophysiological principle: "Every change in the physiological state is accompanied by an appropriate change in the mental emotional state, conscious or unconscious, and conversely, every change in the mental emotional state, conscious or unconscious, is accompanied by an appropriate change in the physiological state." [5]. This concept has been extensively studied and developed in the last decades, thus supporting the notion that any physical or emotional stresses are associated with various physiological and psychological responses [6]. This is evident for conditions in which the human body is submitted to both psychological and physiological stresses, such as during any types of physical exercise, with particular emphasis during competitions.

Among a variety of indicators of stress, elevated heart rate and high state anxiety are considered two of the most important parameter to monitor stress status. The literature indicates that the effects of physical and emotional stress on heart rate response have been investigated among various athletes and disciplines. For example heart rate responses to physical and emotional stress have been reported for automobile drivers [7], archeries [8], and parachuting athletes [9]. However, most of the studies that investigated the response to the stress of parachuting focused on physiological or psychological indices of stress (such as heart rate and anxiety, respectively) [10]. Only very few studies adopted a combined approach, matching the two types of measure. For example, the study by Falk and Bar-Eli [10] examined the psychophysiological stress responses to parachuting using the two common indicators of stress such as heart rate and state anxiety. This approach allowed the authors to investigate the interaction between the two indices, thus supporting the central idea of the psychophysiological principle, formulated by Green et al. [5]. Measuring physiological variables, technologies and instruments play an important role in psychophysiology thus gathering information on the processes occurring in the brain and the body of an exercising subject.

In this sense, the aim of this chapter is to briefly describe the methods actually used in psychophysiological studies in the sport and exercise field, with particular interest in thermal biofeedback. As regard, we propose infrared thermography as potential methodology for studying emotional responses in the field of assessment of psychophysiological states in sport and exercise by means of the thermal signature of such states.

9.2 Biofeedback Modalities in Sport and Exercise

9.2.1 Overview of the Biofeedback Modalities in Sport and Exercise

Scientists and practitioners investigating the psychophysiological response to exercise of human body can apply three different levels of measurement: verbal measurement (e.g., expressions of subjective experience), motor measurement (e.g., particular movements of the body, facial expressions, observed behaviour during training or competitions), and physiological (e.g., electromyography activity, galvanic skin response, heart rate, skin temperature) [11].

The act of monitoring the body's physiological responses of an individual and displaying him this information is denoted as biofeedback [12]. In this sense, biofeedback helps the subject to detect and control physiological functions by using monitoring devices. The basic concept is to provide individuals with information about the inner status of their bodies, brains, and their interaction [13].

Although the development of new technologies and instrumentations especially in the last decades, investigations in the field of psychophysiology and biofeedback are usually conducted in well-controlled conditions, such as laboratory settings. Biofeedback devices and the related modalities are usually used to train people to better control their physiological processes within controlled laboratory setting, rather than for being used during real situations, such as competitions. As regard, biofeedback research has traditionally focused mainly on closed skill sports, rather than on open skill sports [14].

In general, biofeedback is considered from the scientific community a useful tool for stress management and control. However, demonstrating a direct relationship between biofeedback training and performance is not simple because of the variety of factors that contribute to the outcome of the performance [11, 14–17]. As regards, studies that have been conducted on this issue with aim to test the efficacy of a period of biofeedback training have indicated that training with biofeedback contributes to decrease both physiological and self-determined stress levels [11, 18], which may be indirectly beneficial for performance.

A major application for biofeedback is detecting and helping in the management of psychophysiological arousal, in particular in those situations characterized with over arousal. Examples are situations in which athletes are requested to perform a task in a real competition scenario. The situation may exacerbate when the task is crucial for the result of competition, and in turn, its outcome determines conditions of winners or losers [19]. These conditions may be found in both team and individual sports where concentration and psychological states play a fundamental role. Specifically, the condition during which an athlete is under pressure has been defined as choking [20].

The relationship between arousal states and performance has been described and explained by sport psychology using the inverted-U hypothesis [21]. This theory states that at low arousal levels, performance will be below par because the exerciser or athlete is not activated enough from a psychological point of view. As arousal increases, performance will reach an optimal point which of consequence results in the best performance. However, further excess increases in arousal cause a following decrement in performance. In this way, this theory can be represented by an inverted U. In fact, high performance will be reached with the optimal level of arousal, whereas lesser performance with either low or very high arousal.

Physiological processes associated with a status of over arousal and chocking include different modalities of responses, such as tension on skeletal muscle, electrodermal activity, and peripheral vasoconstriction. These are the most used biofeedback modalities [11, 12].

The term “Biofeedback modalities” refers in particular to different types of instrumentation used for recording and monitoring different physiological signals. Several biofeedback modalities have been used in sport and exercise, depending on the situations, each one with its own characteristics. Examples are the measurement of muscle activity and tension by electromyography, the measurement of electrodermal and sweat gland activities, the measurement of the brain’s electrical activity by electroencephalography, the measurement of heart rate and heart rate variability by electrocardiography or heart rate monitor, the measurement of peripheral skin temperature as an index of skin blood flow (see Table 9.1 for a resume of the most common biofeedback modalities). As result, biofeedback training with one or more

Table 9.1 Most common biofeedback modalities, together with the measured variables and the sensors

Biofeedback modalities	Measures	Sensor
Electromyography	Muscle activity, tension, and dysfunction	Electrodes on muscle area of tension
Electrodermal activity	Galvanic skin response, sweat gland activity	Contact sensors on fingers or hand palms
Electroencephalography	Electrical activity of the brain	A scalp cap on the head
Electrocardiography or heart rate monitor	Heart rate, heart rate variability	Sensors and heart rate belt on the thorax
Thermal	Skin temperature	Contact sensors or infrared thermography

modalities combined together has been used both by researchers and practitioners to study the possible improvement in performance of athletes in different disciplines via psychoregulation mechanism [2, 17, 18, 22, 23].

Before presenting the thermal biofeedback and in the following sections proposing infrared thermography (IRT) as a potential method for investigating psychophysiological states in sport, we dedicate space to two other biofeedback modalities that, for their nature of being applied on the surface of the body, are the more ones related to the thermal biofeedback.

In the following paragraphs, we therefore provide a brief explanation and proper examples of electromyography activity biofeedback and electrodermal activity biofeedback. These biofeedback modalities are usually used in combination with the thermal biofeedback.

9.2.2 Electromyography Activity Biofeedback

Measurement of the electrical activity preceding and occurring during muscle contraction is called electromyography. Electromyography quantifies the electrical energy discharged by the motor nerve that induces a muscle contraction [24]. Generally, surface electrodes are positioned on the skin over the muscle of interest. Electromyography biofeedback consists in recording and showing the electrical activity of the target muscle to the subject [25]. Specifically, quantification of electrical activity can be shown to the subject either with visual signals or with auditory signals. Furthermore, the combination of both visual and auditory information is possible [11]. In this way, electromyography provides the subject with a reliable indication of muscle tension. The most common application of electromyography biofeedback is to evaluate the efficacy of periods of electromyography biofeedback training. The aim is therefore to verify that a control of self-regulation has been achieved for a given criterion.

An interesting example of electromyography biofeedback application can be found in the study of Blumenstein and colleagues [26]. In that study, a combination of three psychoregulative procedures of relaxation and excitation with biofeedback were provided to subjects with the purpose to investigate their role on physiological performance variables. A sample of thirty-nine students were assigned to three groups of psychoregulatory treatment (i.e., autogenic and imagery training; music and imagery training; autogenic, music and imagery training). Moreover, a placebo group and a control group were also included in the study. Imagery training consisted on a 100 m run task. The treatment and control conditions lasted 13 sessions of 20 min each. Only in the last 6 sessions, training was accompanied by electromyography biofeedback. It was found that the combination of biofeedback with autogenic, imagery and music training produced a significant augmenting effect on physiological components and athletic performance [26].

9.2.3 Electrodermal Activity Biofeedback

Another widely used biofeedback modality is concerned with the electrical activity of the skin surface. It is not easy to determine whether sweat glands were active, or to quantify the sweat produced [12]. However, since sweat contains salts making it electrically conductive, sweaty skin is more conductive to electricity than dry skin. Therefore, skin conductance activity reflects well sweat gland activity. This phenomenon is known as electrodermal activity, and it has historically been known as galvanic skin response.

Galvanic skin response is based on the fact that sweating is controlled by the autonomic nervous system, and skin conductance is an indication of psychological or physiological arousal. When autonomic nervous system is highly aroused, it reflects his activity by increasing sweat gland activity, which in turn increases skin conductance. In this way, skin conductance can be considered a reliable measure of emotional and sympathetic responses to emotional stimuli of affective nature [27].

Galvanic skin response is recognized as a method to gain objective access to psychophysiological arousal. Electrodermal activity is usually monitored and quantified by contact biofeedback instruments. A galvanic skin response device applies a very small electrical pressure (voltage) to the skin, measuring the amount of electrical current that the skin will allow to pass. Galvanic skin response device is typically applied on the fingers or the palmar surface of the hand (where there are many sweat glands).

Galvanic skin response biofeedback may be used on its own, or in conjunction with other mental and relaxation techniques to institute a relaxation response that might be used to combat high status of precompetition anxiety that may limit performance [17].

A recent paper by Pusenjak and colleagues [17] examined whether an 8-week biofeedback training period (a combination of various biofeedback exercises, such as breathing, muscle, galvanic skin response, and temperature) could improve the psychophysiological control over competitive anxiety and in turn enhance athletic performance. Participants were divided into two groups: experimental group ($n = 18$), and control group ($n = 21$). Psychophysiological responses (including galvanic skin response) to stress tests were assessed before and after the 8-week biofeedback training period. It was found that a greater number of participants in the experimental group were able to successfully control their psychophysiological parameters, with respect to other subjects of the control group. Specifically, a better regulation of galvanic skin response in the stress tests were found in the experimental group, thus supporting the usefulness of biofeedback training [17].

9.2.4 Thermal Biofeedback

One of the most popular biofeedback modality is thermal feedback (often referred as skin temperature). This feedback, as for the others, is usually transformed and expressed to the subjects in the form of audio and visual signals, which reflects skin temperature modifications [11].

In general, thermal biofeedback provides information on the peripheral circulation. This because skin temperature is a function of skin blood flow [28, 29]. Temperature feedback is usually recorded on the surface extremities of the body (such as distal parts of limbs) [30], but can be also recorded in other parts of the body, such as limb muscles, trunk, or face.

Thermal biofeedback can be used in combination with other biofeedback modalities, such as electrodermal biofeedback (i.e., galvanic skin response) and electromyography biofeedback [11, 12]. In this way, integrating the information of different natures coming from various biofeedback modalities may be beneficial for the subjects, which have the possibility to evaluate their behaviour establishing relationships between different biofeedback modalities signals.

The mechanisms on which the thermal biofeedback is based are related to the sympathetic activity of the central nervous system. It is well known that skin temperature is influenced by both external and internal factors of the body (see Chap. 3 of this book for a detailed description of these factors). Among the internal factors, the cardiovascular mechanisms affecting skin temperature are closely related to the sympathetic activity of the autonomic nervous system [31].

The autonomic nervous system is activated when the subject experiences particular emotions, thus causing an increase in arousal. When the autonomic nervous system is activated, the smooth muscles surrounding the blood vessels near the skin surface are likely to contract, thus resulting in superficial vasoconstriction. This vasoconstriction cause a decrease in skin blood flow, which in turn accompanies a decrease in skin temperature. Conversely, an increase in skin temperature is caused by vasodilation that results from the relaxation of sympathetic activity, and in particular from the relaxation of the autonomic nervous system [31].

Biofeedback training finds a role in the link between skin temperature modulation, and activation of autonomic nervous system. Learning to modulate peripheral skin temperatures has been widely investigated through the application thermal biofeedback training. Thermal biofeedback aims to teach individuals to consciously and voluntarily adapt their skin temperature, without medication or external application [30]. The efficacy of thermal biofeedback training has been investigated and proven. For instance, self-regulation of peripheral skin temperatures by people affected by Raynaud's phenomenon has been shown to be particularly beneficial since their ability to control and adapt skin temperature of limb extremities is often scarce [32]. Moreover, individuals with migraine headaches also have shown improvements after learning to relax by increasing distal skin temperatures via thermal biofeedback training [33].

With particular regard to sport and exercise, studies involving thermal biofeedback modalities are scarce. However, it is worth noticing that thermal biofeedback training was applied and studied for self-regulation of skin temperature extremities in sport activities characterized by cold weather (i.e., skiing, ice-hockey, ice-skating, curling, football, mountaineering) [30, 34].

An interesting study was conducted by Kappes and Chapman [30]. The authors examined the effects of indoor versus outdoor thermal biofeedback training on self-regulation of digital skin temperature, measured by contact sensors, in outdoor sports. Moreover, the accuracy of self-estimation of skin temperature after the training period has been also investigated. A sample of 25 individuals were randomly divided into three groups: indoor subjects trained exclusively indoors, outdoor subjects trained exclusively outdoors, and control subjects, which did not receive any training. Subjects of the two experimental groups trained twice a week for four consecutive weeks. Pre and post tests were performed in an unheated tent outdoor. Results indicated that outdoor trained group performed better than the two other groups. Interestingly, there was no significant difference in overall temperature between groups, whereas all subjects overestimated their temperatures when requested to give an estimation. The authors concluded proposing the notion that learning to control skin temperature of distal parts of the body in cold environments may depend on environmental context [30].

9.3 Infrared Thermography as Potential Ecological Method for Assessing Psychophysiological States in Sport

Classical instruments employed for monitoring psychophysiological and emotional states through the thermal signal of autonomic activity usually requires contact sensors or devices (such as thermistors and thermocouples), thus resulting somehow invasive and potentially biasing the estimation of the state of the subject. This is because the compliant participation of the subject in the measurement is required (please see Chap. 5 for further details on contact thermal sensors and IRT comparison).

In the last decade, IRT has been proposed as a potential method for non-invasive and ecological recording of autonomic nervous system activity [35]. IRT, in fact, allows the contact-less and completely non-invasive recording of the skin temperature through the measurement of the thermal radiation of the body [36, 37].

Bioheat exchange is controlled by the autonomic nervous system, which plays a fundamental role in the modulation of various physiological processes, such as heart rate, breathing, tissue metabolism, perspiration, respiration, and skin blood perfusion, particularly during exercise. Therefore, autonomic nervous system can be considered an effective tool for observations of emotional responses and affective states [37]. The potentialities of IRT as a method for non-invasive and ecological recording of autonomic nervous system activity have been widely demonstrated, as IRT is now well recognised by the scientific community of psychophysiology [36–38].

Previous studies have demonstrated that IRT was able to characterize competing subdivisions of the autonomic nervous system [38–40]. Thermal imaging in the field of psychophysiology is usually performed on the facial area of individuals. This because the face is the body part usually exposed to social communication and interaction with the external world. The reliability and validity of IRT in the detection of psychophysiological states was investigated by comparing data recorded simultaneously by thermal imaging and by golden standard methods, such as electrocardiography, piezoelectric thorax stripe for breathing monitoring or nasal thermistors, galvanic skin response. As regards to the latter, studies have demonstrated that IRT and galvanic skin response have a similar detection power [41, 42].

An almost exclusive feature of IRT is its non-invasiveness. This feature makes IRT a powerful tool for research in stress field. In a recent study, Engert and colleagues investigated the ability of IRT in detecting conditions of stress [43]. Thermal imprints were compared to established stress markers (i.e., heart rate, heart rate variability, finger skin temperature, α-amylase, and cortisol) in healthy subjects participating in two standardized laboratory stress tests: the cold pressor test [44] and the trier social stress test [45]. Although the thermal imprints of different regions of the face and stress marker outcomes demonstrated poor correlations, the thermal responses correlated with stress-induced mood changes. On the contrary, the established stress markers did not correlate with stress-induced mood modifications. Overall, the authors concluded supporting the notion that IRT can be a useful tool for the estimation of sympathetic activity in the field of human stress and emotional research.

A more recent study by Di Giacinto et al. [41] examined fear conditioning in posttraumatic stress disorder using both IRT and galvanic skin response. The authors examined fear processing in posttraumatic stress disorder patients with mild symptoms and in individuals which did not develop symptoms (both groups were victims of a bank robbery), through the study of fear-conditioned response. Based on the positive results of the study, it was concluded that the analysis of facial thermal response assessed by IRT during the conditioning paradigm is a promising psychometric method of investigation, even in the case of low level of posttraumatic stress disorder symptom severity [41].

Moreover, IRT was also proposed as a potential tool to create an atlas of the thermal expression of emotional states by using proper classification algorithm [46, 47]. This would be based on the characterization of the thermal signal in facial regions of autonomic valence (nose or nose tip, perioral or maxillary areas, periorbital, and supraorbital areas, forehead), thus monitoring the modulation of the autonomic activity.

A recent paper by Ioannou et al. [36] summarised twenty-three experimental papers that employed IRT for investigations of affective and emotional nature. Moreover, the authors provided a detailed portrait of the adopted experimental protocols and the thermal changes that occurred on selected regions of interest [36].

Table 9.2 Overview of the direction of the skin temperature variation in different regions of interest in response to different emotions

Regions	Emotions							
	Stress	Fear	Startle	Sexual arousal	Anxiety	Joy	Pain	Guilt
Nose	↓	↓		↑		↓		↓
Cheeks			↓					
Periorbital			↑	↑	↑			
Supraorbital			↑		↑			
Forehead	↓↑	↓		↑	↑		↓	
Maxillary	↓	↓	↓				↓	↓
Neck–carotid			↑					
Tail	↓							
Fingers/palm		↓					↓	
Lips/mouth				↑				

Adapted and modified from Ioannou et al. [36]

Interestingly, the majority of the studies have observed that, when autonomic nervous system is activated in response to a specific emotion or affective stimulus, the temperature of the nose tip (indicated by the authors as the most sensible facial area) tended to decrease, attributing this effect to vasoconstriction mechanisms and to the restriction of the skin blood flow.

Similar to what happened to the nose area, a decrease in skin temperature have been observed also on the upper lip or maxillary area, reflecting sweat gland activation. Conversely, an increment in skin temperature have been observed on the forehead and in the region between the eyes and the nose. Overall, a specific direction of the skin temperature change has been found for specific emotion and stimuli. To clarify this point, we report here a modified table of that paper, which provides an overview of the direction of the skin temperature variation in the considered regions of interest in response to different emotions [36] (Table 9.2).

9.3.1 *Methodological Aspects of IRT in Psychophysiology*

As indicated by the review of Ioannou et al. [36], the most used region of the body for investigating thermal expression of emotional states is the face [38, 41–43]. Facial thermal prints provide a useful channel for studying psychophysiological states. To extract information of affective nature from a thermal image series, ROIs are selected in specific regions of the face. The most common region used in psychophysiological studies is the nose or nose tip.

In fact, it has been shown that the nose tip temperature depends on the activation of the sympathetic nervous system in response to emotional stimuli and reflects sympathetic alpha-adrenergic vasomotor effects [40, 41, 47–49]. Furthermore, sympathetic stimulation of the blood vessels in the nose can also have smaller

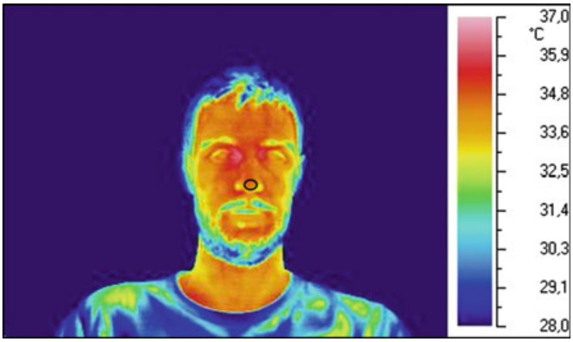

Fig. 9.1 Thermal image of a representative subject's face. The *black circle* indicates the nose tip region usually selected as region of interest in studies assessing psychophysiological states

vasodilatory effects via the action of cholinergic and beta-adrenergic receptor [50]. Figure 9.1 shows an example of thermal image with a male subject's face, and the region of interest positioned on the nose tip. As regard to the choice of nasal area, Di Giacinto and colleagues [41] explained why they decided to focus analysis on the nose tip in the caption of Fig. 2 of that paper. We report here this figure with relative caption modified (Fig. 9.2). In particular, they recorded thermal images pre and post an acoustic stimulation. A general skin temperature decreased could be observed over the whole face. However, they stressed that the skin temperature

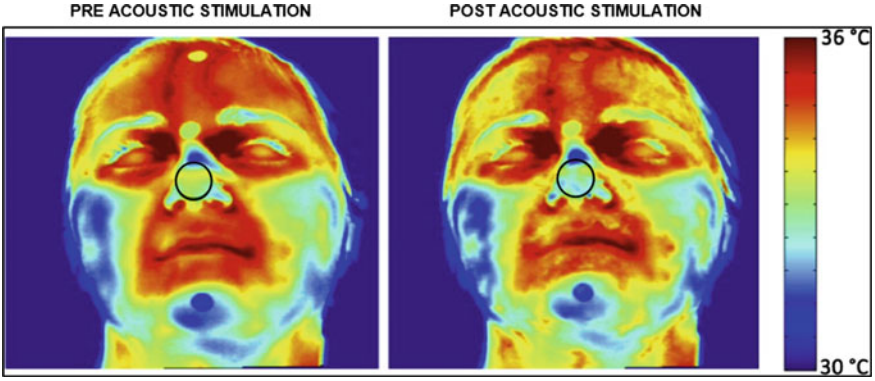

Fig. 9.2 Facial thermal images in a representative subject, before the acoustic stimulation (*left*) and soon after the acoustic stimulation (*right*). A general temperature decrease can be observed over the whole face. In particular, while the cheeks seem not to change their average temperature values and pattern, nose tip, perioral, maxillary and forehead regions clearly present a temperature decrement due to the appearance of colder spots. The temperature decrease is particularly appreciable on the nose tip, where blue areas can be easily spotted. The *circles* over the face are paper markers put on to facilitate the tracking of the region of interest along the procedure. The black-contour circular region on the nose tip is the region of interest used to extract the temperature data. Figure adapted and modified from Giacinto et al. [41]

Table 9.3 Overview of the studies in psychophysiology using IRT to estimate autonomic nervous system activity

Author	Year	N	Emotion	Experimental paradigm	Baseline	Regions of interest
Calvin and Duffy	2007	33	Stress	Driving/mental loading task	Rest	Forehead, nose
Pavlidis et al.	2012	17	Stress	Laparoscopic drill training	Natural landscapes	Perinasal
Puri et al.	2005	12	Stress	Stroop test	Rest	Supraorbital vessels
Kang et al.	2006	9	Stress	Alphabet arithmetic task	Rest	Forehead, nose
Mizukami et al.	1990	34 (pairs)	Stress	Mother–infant separation stress/stranger exposure	Held by mother	Forehead
Kistler et al.	1998	20	Fear	Horror movie	Prestimulation	Fingers
Merla and Romani	2007	10	Fear	Electric stimulation and trigger	Prestimulation	Face, palm
Shastri et al.	2012	10	Startle	Glass breaking, phone ringing	Mental task-counting circles	Periorbital, supraorbital, maxillary
Naemura et al.	1993	52	Startle	White noise (45–100 dB)	Comparison between groups	Nasal region
Pavlidis et al.	2001	6	Startle	Loud noise (60 dB)	Rest, sit quietly in a dark room	Periorbital area, cheeks, neck area
Gane et al.	2011	11	Startle	Loud noise (102 dB)	Image-matching task	Periorbital
Ebisch et al.	2012	12 (dyads)	Empathy	Toy mishap	Playing with toys	Face: nose, maxillary
Manini et al.	2013	18 (dyads)	Empathy	Toy mishap	Playing with toys	Face: nose, maxillary
Ioannou et al.	2013	15	Guilt	Toy mishap	Playing with toys	Nose
Hahn et al.	2012	16	Sexual arousal	Touch on high intimate regions	Neutral face presentation	Nose, lip, periorbital
Merla and Romani	2007	10	Embarrassment	Presence of strangers while performing a mental task	Prestimulation	Maxillary, face, palm

(continued)

Table 9.3 (continued)

Author	Year	N	Emotion	Experimental paradigm	Baseline	Regions of interest
Nakanishi and Matsumura	2008	12	Laughter	Playing	Prestimulation/acclimatization	Nose, forehead, cheek
Pavlidis et al.	2002	12	Anxiety	Mock interrogation	Prestimulation	Face
Tsiamyrtzis et al.	2006	39	Anxiety	Mock interrogation	Prestimulation	Periorbital vessels
Zhu et al.	2007	38	Anxiety	Mock interrogation	Prestimulation	Supraorbital vessels

The table indicates the baseline and the experimental approach followed to induce the emotion of interest. The last column indicates the region of interest in which thermal observations were made. Adapted and modified from Ioannou et al. [36]

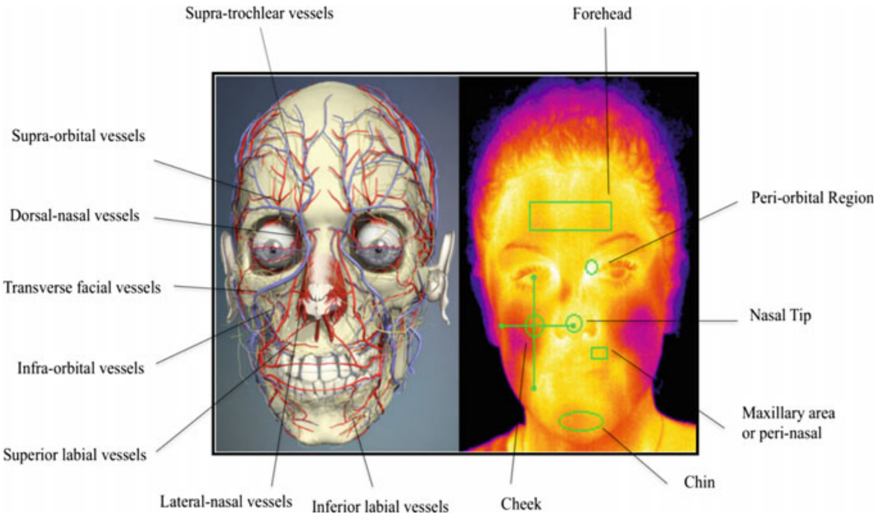

Fig. 9.3 Vascular representation of the major subcutaneous vessels affecting the skin temperature of the face (*left panel*). Thermal representation of the face with the most common ROIs (*right panel*). Figure modified from Ioannou et al. [36]

decrease was particularly appreciable on the nose tip, where blue areas can be easily spotted. Therefore, temperature data were extracted from a region of interest on the nose tip.

However, apart from the nose, the literature reported also other regions that have been studied, such as forehead, the inner cantus of the eye (peri-orbital area), the maxillary area and the lips, the cheeks, carotid, as well as fingers. An overview of the studies in the literature using IRT to estimate autonomic nervous system activity is provided in Table 9.3.

Figure 9.3 shows a schematic representation of the most common ROIs used in psychophysiological states assessment, together with a vascular representation of the major subcutaneous vessels affecting the skin temperature of the face.

9.3.2 *Future Directions of Research in Sport Psychophysiology Using IRT*

All in all, although the actual increasing use of IRT for investigating affective and emotional nature with various experimental paradigms, none of the studies summarised and presented in the review by Ioannou et al. [36] employed conditions involving sport and exercise activities (Table 9.3). In fact, to the best of our knowledge, to date there are no studies that have applied IRT in psychophysiological states assessment in the sport and exercise scenario.

However, analysing and extrapolating the findings of the examined studies, in particular focusing on the study by Ioannou and colleagues [36], together with the methodologies employed, it is reason to hypothesize that IRT may be a useful tool in the field of emotional research in sport and exercise settings. Specifically, we suggest the use of IRT in those activities that cause null or limited activation of thermoregulatory processes, such as golf, curling, archery, and shooting, where the concentration and the psychological components are maximized, thus in turn maximising the activation of the autonomic nervous system.

Furthermore, the application of IRT to study the autonomic nervous system activation in other kinds of sport activities is also possible. For example, game sports activities can be beneficial of the use of IRT for assessing psychophysiological states. This application may be restricted to particular phases of the game, such as penalty kick in football, and free throws in basketball, when thermoregulatory processes as well as movements of the subjects, especially the face, are negligible.

Neverthless, cautions are needed in planning studies on these sports activities because of the activation of thermoregulatory processes, which may act as confounding factors of the thermal signal coming from autonomic nervous system activation, thus creating possible difficult interpretations of the thermal data. Moreover, difficult in its application can be related to the experimental setting, giving the fact that strategies should be adopted to position the thermal camera in a non-laboratory setting and in a non-controlled environment.

9.4 Benefits and Limitations of Infrared Thermography for Assessing Psychophysiological States in Sport

As for every tools, IRT have both benefits and limitations that should be considered before planning any kinds of psychophysiological experiments in the sport and exercise field. In this paragraph, we provide a general overview on the actual literature about the most significant benefits and limitations characterizing the use of IRT in psychophysiology research, with particular interest in psychophysiology of sport.

Over the years, and especially in the last decades, the sensitivity and resolution of the thermal camera have dramatically improved [51]. In fact, physiological events that would be invisible to the naked eye, such as activation of perspiration pores, can now be detected and documented by use of thermal infrared imaging [52].

Infrared cameras allow wireless recordings of skin temperature, from a distance, without interfering with the subject's behaviour and the experimental setting, and despite the possible subject's movements [36, 51, 53, 54]. Likewise, also the development of software for analysing thermal images and extracting temperature values have increased the possibility of using IRT in sport and exercise studies. In fact, thanks to the solutions provided by tracking the regions of interest, it is possible to follow the body area under investigation avoiding any contacts with the subjects, and without the use of any markers on the skin [55]. This great potentiality can contribute to the diffusion of IRT not only in psychophysiology research, but also in sport and exercise research, where the movement of subjects makes difficult the acquisition of thermal images and their following analysis.

Another advantage lays in the fact that, with respect to galvanic skin response, IRT provides the same physiological recording efficiency reflecting accurately the autonomic nature of the psychological phenomenon during the experimental procedure without any direct contact. In fact, it has been noticed that galvanic skin response electrolytes can change conductivity over time [56], both spontaneously during baseline recordings [57] or during non-steady state phase reflecting stimuli [58].

Moreover, galvanic skin responses are so sensitive to emotional stimuli that reach maximum activity levels in conditions of different degrees of intensity, making them indistinguishable from each other, which is a problem that IRT overcomes [48]. This notion was supported also by Kreibig [59] which stated that studies investigating of autonomic nervous system response to emotion have been impeded by the quasi-exclusive use of common physiological measures, such as heart rate and electrodermal activity. These variables have been used as sole indicators of the activation state of the organism [59].

On the other hand, it is necessary to highlight that, although the advantages offered by IRT, limitations are also present and should be known by researchers which are going to study emotional states using IRT.

First, it is worth noticing that the thermal signal of the skin in response to a general stimulus is quite slow, also with respect to the skin conductance. Therefore, the slowness of the thermal signal, which occurs by the result of microvascular change, perspiration, or muscular activity, may be a limitation of IRT. As regard, Kuraoka and Nakamura [48] in their paper stressed the fact that IRT has a longer latency with respect to skin conductance in response to a stimulus. Specifically, it has been shown that the earliest that temperature changes can be observed is within 10 s from the stimulus, whereas changes in skin conductance are evident in only 3 s from the stimulus [38, 48].

Most studies investigating emotional responses with IRT have focused on the skin temperature of the nose, which is considered a region of the face particularly sensible and reliable for identifying thermal signal of psychological states [48, 60]. However, despite the large use of the nose as region of interest, controversies exist in the literature about the cause of the observed temperature change on the nasal area. In fact, the changes in skin temperature of the nose have been attributed to the act of breathing, especially with heavy breathing, and not only to activation of autonomic nervous system [35].

Therefore, it is difficult to exclude the fact that nasal skin temperature changes are not due to airflow patterns or blood flow modifications associated to muscular activity of the facial muscles. Nevertheless, nose temperature changes have been clearly shown to respond to stimuli of affective and emotional nature [49], thus providing evidence to support monitoring of the thermal signal of the nasal area as reliable indication of autonomic nervous system activation.

Finally, it is worth noticing that IRT was a quite expensive tool for monitoring skin temperature and microcirculation, thus making its prevalence in studies scarce. However, especially in the last decade, development in infrared instrumentation technology of both thermal camera and related computer software, as well as the consequent lowering prices, have contributed to the diffusion of thermography in psychophysiology.

9.5 Computation of Psychophysiological Signals from Infrared Thermography

Conventional approaches for assessing psychophysiological states are based on the measurements of physiological variables reflecting the sympathetic activity, in particular the autonomic nervous system activity. As regard, most of the physiological variables measured in psychophysiological studies usually required the application of contact sensors, such as electrodes, probes, and belts. It is therefore evident that these sensors may have also limitations because of their nature to be in direct contact with the body of subjects. Moreover, in complexes physiological studies, many variables may be monitored at the same time to study their relationship in response to a stimulus. In this sense, more variables to be assessed, more contact sensors to be positioned on the body of subjects at the same time. This certainly has negative implications on the comfort of the subjects during the experimental protocol, from both physical and psychological points of view.

Recently, IRT has been proposed as a useful solution for non-invasive and ecological recording of thermal signature indicating activity of the autonomic nervous system. Since the face is naturally exposed to social communication and interaction, thermal imaging for psychophysiology is generally performed by recording images of the subject's face [36, 37, 54].

In order to exceed limitations related to the use of thermal contact sensors, computational psychophysiology based on thermal imaging modelling approach has been proposed and introduced in the literature [55]. Therefore, IRT has found an application also in the computation of varies physiological signals from its thermal signals.

Different psychophysiological signals can be identified and indirectly calculated through analysis of thermal signatures of the face in response to emotional and stress stimuli. Specifically, it has been demonstrated that the application of bioheat transfer models to thermal signals by IRT allows computing different physiological variables, such as heart rate, breathing rate, and cutaneous blood perfusion. In this section we present briefly the possibility of computing heart rate, breathing rate, and cutaneous perfusion from the analysis of a series of thermal images. For more details on models presented, we suggest to refer to the review by Cardone et al. [55].

One of the most used signals in psychophysiology is heart rate. Analysis of thermal signals provided by IRT allows the computation and the quantification of the heart rate at distance in a completely non-invasive way thanks to the modeling of the pulsatile propagation of skin blood flow [39, 61, 62]. In fact, the heart contraction during the ventricular systole induces a pressure wave, which propagates through the arterial tissue. Arterial pulse reflects the heart activity thus providing a measure of cardiac interbeat intervals, heart rate, and its variability [63]. The method proposed is based on the information of the thermal signal of major superficial vessels (e.g., carotid, supraorbital, temporal), recorded through a highly sensitive thermographic system (Fig. 9.4).

Breathing consists of continuous inspiration and expiration cycles during which heat is exchanged with external environment by airflows through nostrils. These exchanges create a quasiperiodic thermal signal in proximity of the nostrils that varies between high (expiration phase) and low (inspiration phase) skin temperature values. In fact, it has been shown that, instead of the classical thermal contact sensors, this phenomenon can be captured and monitored by IRT at distance, with an accuracy of 96.43% [64]. The estimation of breathing rate through thermal

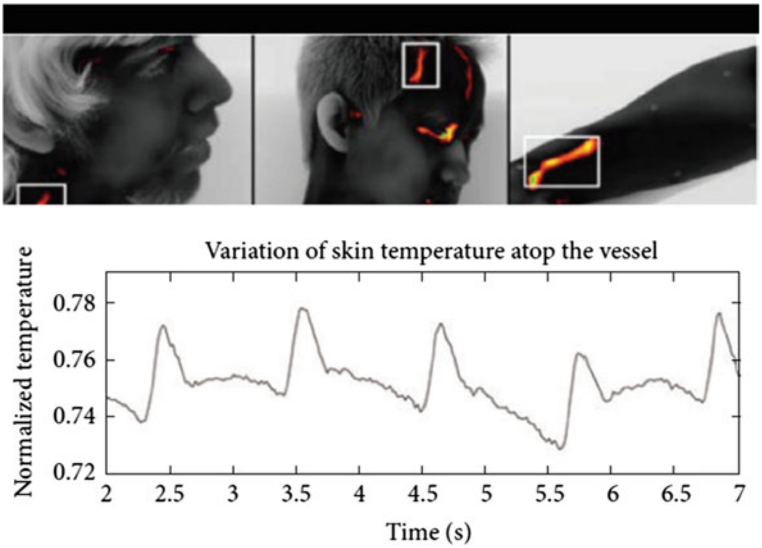

Fig. 9.4 Heart rate computation from thermal images data. Recording point on the carotid arteriovenous complex, the frontotemporal region, and the wrist (*upper panel*). Skin temperature dynamic after removing frequency signals lower than 0.67 Hz (40 beats min^{-1}) and higher than 1.67 Hz (100 beats min^{-1}). Figure adapted and modified from Garbey et al. [39]

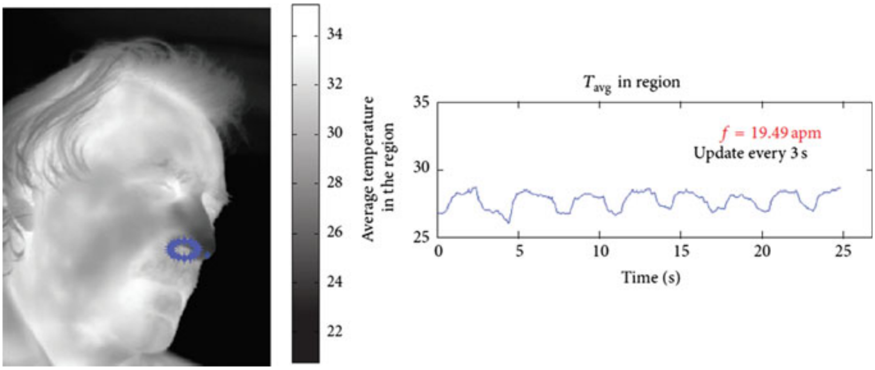

Fig. 9.5 Thermal image of a subject with the track of the airflow on a region of interest on the nostril (*left panel*). Dynamic of average temperature of the region of interest close to the nostril. Figure adapted and modified from Cardone et al. [55]

imaging was found to be very accurate, as proved by studies that have compared with respiratory signals recorded by conventional sensors [65, 66]. Example of computation of breathing rate from thermal signal is shown in Fig. 9.5.

It has been demonstrated that also cutaneous perfusion can be computed from high frequency series of thermal images recorded on a specific region of the body [67]. This is because cutaneous temperature modification within a short time is mainly due to the heat gain/loss by convection attributable to blood flow of cutaneous blood vessels and the heat conducted by subcutaneous tissue. The model showed that cutaneous blood flow depends mostly on the time-derivative of the cutaneous temperature, and on the difference between the temperatures of the cutaneous layers and the inner tissues [67]. The method proposed by Merla and colleagues has been validated by comparison with laser Doppler imagery [67]. This study produced evidence that it is possible to transform series of raw thermal images in a series of cutaneous blood flow image (Fig. 9.6).

Above-mentioned studies support the value of IRT for estimating and monitoring physiological variables such as heart rate, breathing rate, and cutaneous blood perfusion. Reliability and validity were proven by comparing data simultaneously recorded by IRT and by golden standard methods, as piezoelectric pulse meter for heart rate monitoring, piezoelectric thorax stripe for breathing monitoring, nasal thermistors, and laser Doppler imagery. Therefore, we feel to support the use of IRT as a powerful and ecological tool for computational physiology.

However, researchers interested in estimating physiological variables from series of thermal images should have caution in generalizing these findings to the sport and exercise field. In fact, the studies that have assessed the value of IRT for estimation of other physiological variables did not include exercise conditions. Exercise creates a non-steady state condition during which phenomena of various nature happen in the human body.

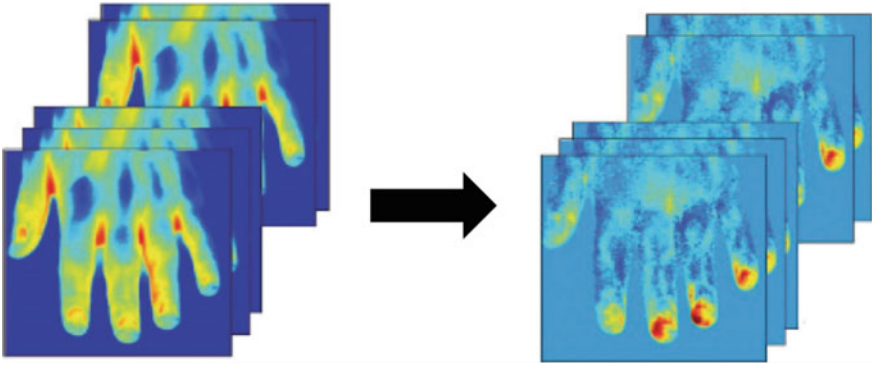

Fig. 9.6 From thermal image series to cutaneous blood flow images. Thermal images is converted into a series of thermal images-cutaneous blood flow images by applying computational models for bioheat exchange. Figure adapted and modified from Merla et al. [67]

Therefore, in addition to the above paragraph on future directions of research, we would like to stimulate researchers in planning and conducting investigations aiming to compare data simultaneously recorded by IRT and by golden standard methods for assessing physiological variables under non-steady state exercise conditions. For example, we feel to suggest the study of the comparison of data recorded by IRT and golden standard methods during well-controlled laboratory human performance. Incremental maximal exercise and submaximal steady-state exercise at different intensities on cycle ergometer and treadmill can be used as exercise stimuli triggering non steady-state condition.

The findings of these future studies can contribute to fill a gap in the literature, which may extend the use of IRT in sport and exercise psychophysiology, not only for measuring skin temperature, estimating skin blood flow, and estimating the autonomic nervous system activity, but also for measuring other physiological variables, such as heart rate and breathing rate, in a completely non-invasive way.

9.6 Conclusions

In this chapter, we presented a general overview on the literature about the potentialities of IRT in the assessment of psychophysiological states in the sport and exercise scenario.

Despite the lack of studies in the literature, IRT may provide an alternative ways for addressing questions regarding autonomic nervous system function in response to exercise and emotions that have so far been unexplored. In particular, considering the present literature about the application of IRT in psychophysiology, it is reasonable to hypothesize that IRT may become a useful tool in the field of emotional research in sport and exercise settings.

In the light of the above-mentioned evidences, we feel to propose IRT as a novel wireless, ecological methodology for quantifying emotional responses in the sport and exercise field. In particular, we recommend its use in those sport activities characterized by low to null thermoregulatory responses. Specifically, we feel to support the use of IRT in those activities that cause null or limited activation of thermoregulatory mechanism, such as golf, curling, archery, and shooting.

Moreover, IRT application to other kinds of sport activities should also be considered. This is particularly promising in game sports activities, especially in specific phases of the game where the movements of the subjects and the thermoregulatory processes are negligible and limited (such as penalty kick in football, and free throws in basketball).

All in all, the maturity and the feasibility achieved in the recent years by IRT in the general field of psychophysiology suggest its use even in the more specific field of sport psychophysiology. However, researchers and practitioners should be aware on the existence of limitations for using IRT, especially in a real-world sporting scenario. Cautions must be adopted by researchers and practitioners in interpreting data to avoid the attribution of any psychological valence to merely thermoregulatory or acclimatization processes.

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Chapter 10
Foot Temperature Assessment

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Abstract Thermographic studies of the foot can be very useful in 3 different ways: in preventing injury, in analyzing sporting technique and in assessing the effects of footwear and clothing. The aim of this chapter is to discuss several methodological points concerning the thermal analysis of the foot using infrared thermography, as well as to discuss how it can be applied to the science of sports, both in areas already researched and those as yet uninvestigated.

10.1 Introduction: Foot Anatomy and Physiology

To understand the possibilities that the analysis of foot temperature through infrared thermography presents to us, we first of all have to know the characteristics of that region of the body. The foot presents a very particular anatomy and physiology for a number of reasons. It has its own vascularization and thermoregulation, as it is one of the most peripheral regions of the body. Moreover, the feet support all the weight of an individual and are subject to considerable forces during physical exercise. We shall, therefore, now provide an introduction to the anatomic and thermophysiological structure of the foot.

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The foot acts as a structural platform that is able to bear all the different loads and movements of the human body [1]. It consists of 28 bones (including the sesamoids) the movements of which are all interrelated [1]. Bone tissue behaves as a good heat sinks due to its porous structure and represents between 28 and 31% of the foot mass [2]. Furthermore, the bones of the foot are laid out in the form of longitudinal and cross-sectional arcs that provide greater support than other layouts would [3].

The structure of the foot is similar to that of the hand, but there are certain differences that allow it to support weight and adapt to different surfaces and speeds of locomotion. For that reason the big toe of the foot is less mobile but has a greater structural solidity [3].

There are two groups of muscles related with foot movement. On the one hand there are the extrinsic muscles of the foot which are located in the leg and exercise their action by pulling on the tendons that are inserted into the ankle and foot [3]. These are responsible for making the movements of dorsiflexion, plantar flexion, inversion and eversion of the foot [3]. These movements, especially eversion of the ankle, have been widely studied through biomechanics applied to sport, as they are the ones most associated with risk of injury [3, 4]. On the other hand are the intrinsic muscles of the foot. These muscles are responsible for the fine movements of the toes such as flexion, extension, adduction and abduction [3].

When the muscles are active, they can release great amounts of energy. In the foot, the extrinsic muscles, located in the leg, are responsible for bigger movements, so there is no great heat source within the foot and, therefore, the thermal energy generated comes from other sources [2]. This fact, together with the higher presence of the heat dispersal structures that the foot possesses (such as the sweat glands or bone tissue), actually facilitates heat loss in that region, so increasing susceptibility to injuries caused by cold [5].

Blood flow is rarely stable in the feet as the thermal changes affect many cutaneous blood vessels [6–8]. Blood supply to the foot comes from arteries that enter behind the malleolus and along the dorsal surface of the foot [9]. Medial plantar artery enters trough the medial malleolus, across the sole and provide blood to the intrinsic muscles of the foot, to the skin of the medial plantar region and to the medial three toes [9]. The external plantar artery feeds blood to the calcaneus and adjacent muscles, to the plantar tarsus and to the tarsometatarsal joints and the lateral zone of the sole of the foot [9]. In the dorsal zone are the medial and lateral tarsal arteries, the arcuate artery and the first dorsal metatarsal artery, which takes the blood to the first and second toes [9]. For their part, the second, third and fourth dorsal metatarsal arteries each supply blood to their own toe and the next one [9].

In the foot, moreover, the draining of the blood takes place from the toes towards the dorsal venous arch (nearer the surface) and the plantar venous arch (deeper) [9]. Venous return takes place through the tibial vein and the foot fascia, which mix with the blood from the dorsal surface before leaving the saphenous veins [2].

The normal state of the veins on the soles of the feet is that of vasoconstriction and consequently the accumulation of venous blood is minimum, a passive dilation of the veins being produced in hot situations [10, 11]. In contrast, there are mechanisms of active vasodilation in the dorsal region that are activated in hot situations [12], such as, for example, during exposure to heat or undertaking physical exercise, where vasodilation, blood flow and perspiration increase, as they are essential for dispersing heat [13, 14]. If, on the contrary, the human body cools down, vasoconstriction is activated, most of the blood flow going to the central areas of the body and reducing the arterial flow to the limbs [2]. In mountain sports where temperatures can be very low and, therefore, great vasoconstriction takes place, cases of foot amputation as a result of freezing are well known [15].

As commented on earlier, perspiration is one of the most important heat dissipating mechanisms in hot surroundings [14]. The sole of the foot has around 467 cm^2 of sweat glands, whereas the dorsal surface of the foot has only 119 cm^2, the sole, therefore, having an 80% concentration as opposed to 20% on the top [2]. Moreover, feet and hands lose more water than the rest of the body (2–4 times more) through the loss of transepidermal water. The dorsal surface of the foot loses ~ 0.05 mg cm^{-2} min^{-1}, whereas the sole loses 0.10 mg cm^{-2} min^{-1} [16].

The foot plays a fundamental role in human thermoregulation as a thermal radiator whenever there is more than sufficient heat transported by the blood to these regions [17]. Thus, knowledge of foot temperature can help us to understand the effects that footwear and exercise have, both on risk and prevention of injuries, and on the sporting performance. Infrared thermography is now considered a valid and reliable technique when it comes to discovering the surface temperature of the skin, provided that the factors that may affect its measurement are controlled and an appropriate methodology to prevent errors of measurement is followed.

10.2 Methodological Aspects Related with Foot Temperature Assessment

As foot temperature is very unstable due to factors that will be explained later on, it is essential to be able to control a series of methodological aspects linked to the assessment of their temperature. That methodological control helps to minimize errors in measuring foot temperature, so increasing the validity and reliability of infrared thermography.

10.2.1 Advantages and Limitations of Infrared Thermography in Assessing Foot Temperature

Measuring foot surface temperature by means of infrared thermography brings with it a series of advantages and limitations. As mentioned earlier, infrared thermography is a quick, accurate, non-invasive and objective method for measuring foot surface temperature [18, 19]. One of the main advantages of infrared thermography is that the measurements are taken at a distance, in such a way that it allows us to see the distribution of temperature in a non-invasive manner and at no risk to the patients [20, 21]. These characteristics make thermography a highly recommended tool when it comes to assessing the temperature of any region of the body, including the soles of the feet.

Furthermore, by measuring the surface temperature of the soles of the feet, a great amount of information can be obtained on the physical, circulatory and thermoregulatory state of the individual being assessed. However, it is important to bear in mind that both skin temperature and limb temperature are very dependent on underlying circulation and the metabolic tissue rate [22]. This may involve inter-individual differences or differences caused by the influence of environmental conditions [23–25].

Similarly, the use of thermography enables us to define the location of the area where an inflammation and/or an injury has taken place [26]. The ability to detect injuries or inflammations through infrared thermography is because inflammatory response is characterized by an increase in the permeability of the blood vessels, which leads to an increased blood flow, so altering the body's heat pattern [26].

Despite that, the dynamic nature of foot temperature regulation and the variability of its reaction to the very same stimulus, with regard to the initial temperature has to be borne in mind [21, 27]. Here, there are multiple factors that make the temperature of the feet vary, such as environmental conditions, the moment of measuring and the physiological conditions of the region that is to be measured, so it is very complicated to establish a significant relationship between the foot and clinical diagnosis or sport intervention [28].

The main advantages as far as other injury-detecting instruments are concerned, such as magnetic resonances or scanners are that infrared thermography does not emit radiation, it works from a distance, it is portable and is low-cost [20, 29, 30]. Nevertheless, as far as foot temperature analysis goes, it has one clear limitation and that is that it is not possible to monitor foot temperature during the foot's daily activity. Being an imaging technique, it is necessary to undertake measurements in laboratory conditions and in most cases undressed and outside the foot's normal habitat, the shoe. This limitation is very evident in the sports setting where, when undertaking physical exercise, athletes usually have their feet covered by socks and footwear, which makes infrared thermography measurements on the soles of the feet, in a dynamic way, impossible.

Regarding sport sciences, thermographic analysis of the foot can offer numerous applications of great interest, as will be explained in this chapter. However, its use in this field is quite recent, so further studies are required that may help to clarify its potential. In the clinical field, the main limitation to thermography is the insufficiency of databases with which to diagnose any type of injury, as, to date, we can only detect the production or recovery from an inflammation and/or injury, but it is still not possible to diagnose it accurately. Currently, therefore, the best way of using thermography is in combination with other techniques, instead of as a replacement of them [29, 31]. By doing so, it can reveal physiological changes that appear before clinical signs appear and enable early diagnosis and intervention [26, 30, 32].

Moreover, on some occasions, it can provide relevant information on other physiological variables that conventional diagnosis techniques (such as magnetic resonance, scanners, etc.) do not take into account [30].

10.2.2 Reproducibility

One of the determinant aspects in measuring the temperature of the feet soles is the low reproducibility of measurements in that region. Skin temperature is more stable in the trunk than in the limbs, where there is high variability that seems to depend on endogenous factors, such as the sympathetic nervous system or the environmental temperature [33].

Furthermore, in the most distal regions of the human body, such as the feet, peripheral circulation is weaker and there is a constant struggle between the mechanisms of vasoconstriction and vasodilation that regulate the blood flow of the skin, so increasing the variability of skin surface temperature and reducing the reproducibility of thermographic measurements in that region [33]. It is for that reason, more important than ever, that we must be able of controlling any extrinsic factor (such as preventing alcohol, tobacco and medicinal intake or avoiding physical exercise before measuring, etc. as stated in Chap. 3 of this book) that may affect the infrared thermography measurements of the feet, so as to reduce the variability of measurements in these regions [33].

With regard to sports studies, where physical exercise is usually undertaken and temperature measured before and after, it would be interesting if future studies could compare the reproducibility of the variation in temperature (difference between pre- and post-exercise) with absolute temperatures. It is possible that, although the reproducibility of the foot is low [33], the effect of exercise may be more constant.

10.2.3 Thermal Imaging of the Feet

There seems to be a consensus about the position for taking thermographic images of the soles of the feet. The images are taken following a period of thermal equilibrium (or adaptation to room temperature), where the participant who is subject to thermal imaging, is positioned sat down with their legs extended (Fig. 10.1).

When the image is to be taken, it is recommendable to place a matt black anti-reflection panel behind the feet so as to minimize the effects of the reflected temperature of the surroundings, and to isolate the image of the foot sole and not capture other regions of the body such as the legs (Fig. 10.2a) [19, 34]. Nevertheless, it is important to bear in mind that the feet (together with the hands) are regions of the human body that present the highest values of radiant heat loss. Hence, these regions at rest (mainly the fingers and toes) usually present very

Fig. 10.1 Recommended position for thermal imaging of the soles of the feet

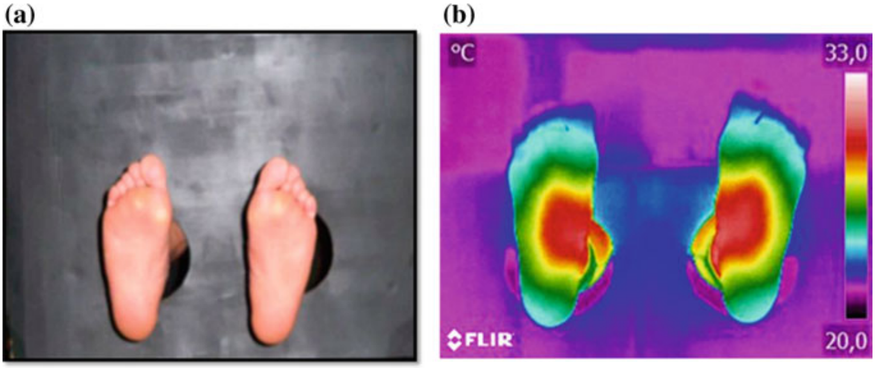


Fig. 10.2 **a** Anti-reflection panel behind the feet of a participant undergoing thermal imaging of the feet soles. **b** Example of a thermal image of toes that present temperatures similar to surrounding room temperature

similar temperatures to the surrounding room temperature where measuring takes place, and it is often complicated to visualize the fingers or toes as they are of such similar temperature to the surrounding temperature (Fig. 10.2b).

Most investigations have not reached an agreement on the time required for participants to remain in this position while adapting to the room. On the one hand, those studies where other regions of interest are measured in which the fact that the individual is seated may interfere, for example the posterior femoral zone, undertake a thermal adaptation period of between 15 and 20 min in anatomic position and once the thermal images of the body are taken, they seat the participant for a further 5 min before taking the thermal images of the feet soles [30, 33]. By doing so, they believe that this is sufficient time for thermal equilibrium to take place in those participants.

On the other hand, in studies that only focus on the soles of the feet, the participants remain in the seated position with their legs extended during the entire period of thermal adaptation [34, 35]. This period must be at least 10 min so as to adapt well to room conditions [29, 36], but it could be longer if the environmental conditions outside the room are of extreme cold or heat, as, in this case, the body needs a longer period to stabilize the temperature [33, 36].

10.2.4 Regions of Interest (ROIs)

Choosing the regions of interest (ROIs) for foot assessment depends on the aims of each investigation. It seems that there is no homogenous definition of ROIs for the foot that can serve for all studies.

Ammer [37] tried to establish a protocol for thermographic analysis of the different regions of the human body, which was called the *Glamorgan Protocol*. Within the 90 regions of interest in the entire body, it established two single regions on feet: the dorsal region and the sole of the foot (Fig. 10.3).

However, many authors do not follow the recommendations of this protocol when it comes to analyzing the sole of the foot, as, by doing so, one loses a large part of the information on what is happening in the different regions of the foot sole. Below we shall present several of the divisions that authors have undertaken both on the diabetic foot and in the medicine and physiology of sport, in an attempt to seek common ground between them.

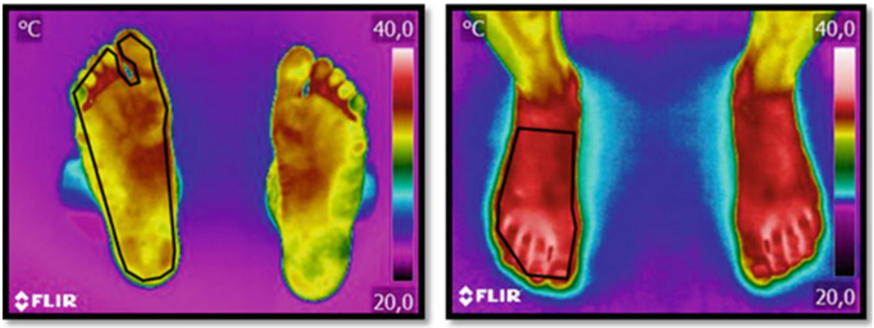


Fig. 10.3 Regions of Interest on the feet according to the Glamorgan Protocol [37]. The foot sole (*left*) and the dorsal region of the foot (*right*)

When studying diabetic foot ulcerations, there are two main ways of dividing the foot sole. On the one hand, some authors [20, 38, 39] opt for dividing the sole of the foot in an anatomic way, which varies depending on the aims of each study. The hallux (big toe), the lesser toes, the metatarsus (which can be separate or together) and the heel typically appear separated (Fig. 10.4). In some cases, moreover, divisions in the arch and the lateral zone of the midfoot appear [39, 40].

On the other hand, some studies [41–45] propose analyzing regions of the feet of diabetic subjects through the concept of angiosome, a region of the foot composed of the tissues irrigated by the same artery of origin [43, 46]. These authors divide the foot sole into 4 zones, in accordance with the medial plantar angiosomes proposed by Attinger et al. [47]: the angiosome of the medial plantar artery (MPA), the angiosome of the lateral plantar artery (LPA), the angiosome of the medial calcaneal artery (MCA) and the angiosome of the lateral calcaneal artery (LCA) (Fig. 10.5).

In the case of medicine and physiology, the division of the regions of interest on the foot sole is more structural. Zaproudina et al. [33] undertook a division of the soles of the feet into 9 regions of interest: the complete sole, three different regions of the arch and heel zone and each of the toes separately, so as to discover the reproducibility of this zone of the human body (Fig. 10.6).

In a recent study, and in the field of sport [34], it was proposed that the division of the regions should follow a commonly used division for analyzing plantar pressure when running: the forefoot (50% of the surface of the foot sole), midfoot (19% of the surface of the foot sole) and rearfoot (31% remainder of surface) (Fig. 10.7). The authors of this chapter would like to add to this division a further 5 regions of interest for future studies: complete foot sole, medial foot sole (50% inner surface of the foot sole), lateral foot sole (50% outer surface of the foot sole), medial rearfoot (50% inner rearfoot) and lateral rearfoot (50% outer rearfoot), as

Fig. 10.4 Example of anatomical division of the diabetic foot according to Sun et al. [39]

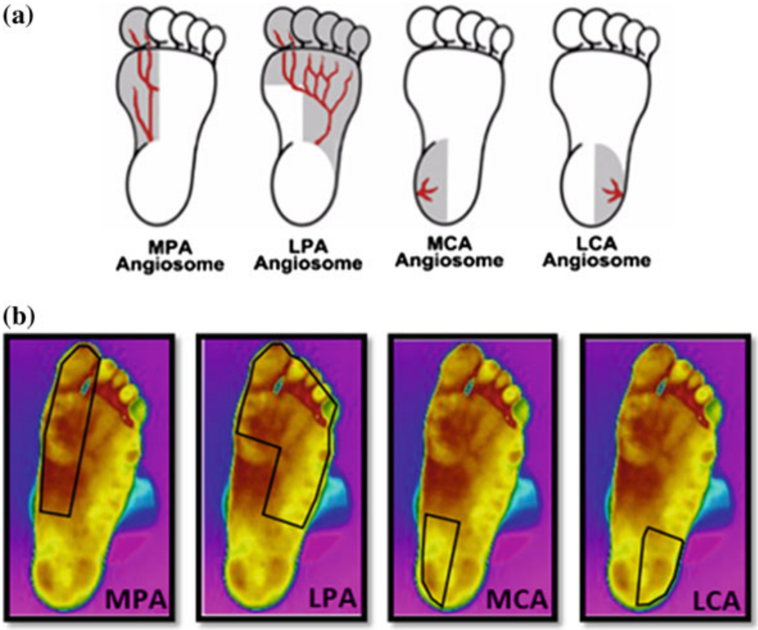
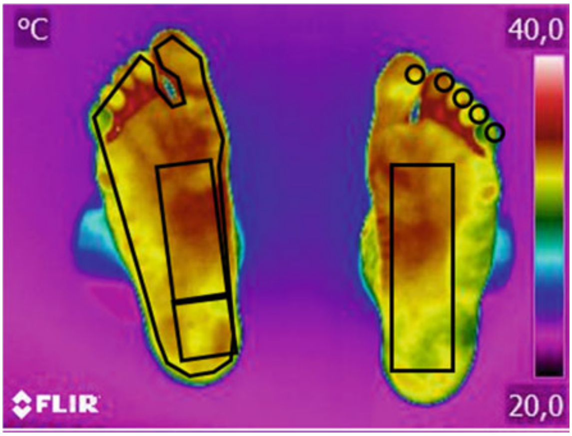


Fig. 10.5 Division of the thermographic image of the sole of the foot (**a**) according to the 4 angiosomes (**b**). Image A obtained from Nagase et al. [43]

Fig. 10.6 Structural division of the foot sole according to Zaproudina et al. [33]



shown in Fig. 10.7. This extra division will provide a deeper analysis of foot temperature with regard to exercise, as well as greater applicability in sport sciences, as will be explained in the following section.

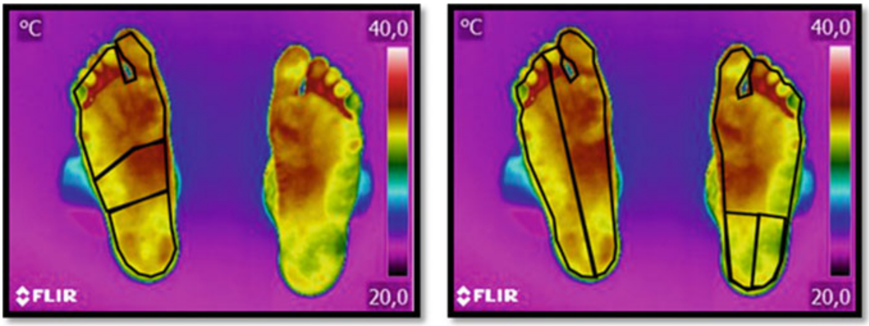


Fig. 10.7 Example of the division of the foot sole depending on the support provided while running according to Priego Quesada et al. [34] (*left*) and the five added region proposed by the authors of this chapter (*right*)

10.3 Applications of Thermographic Assessment of the Foot in Sports Sciences

The use of infrared thermal imaging in sport allows us to undertake rapid assessments, both quantitatively and qualitatively. Following up the thermal response of the sportsman or woman can provide relevant information on their health and on their performance, by contributing to the analysis of the sporting technique [48]. Furthermore, knowing foot temperature may help to understand the effects of footwear and sports equipment, which are also related with the performance and health of athletes [49, 50]. Hence, the following section focuses on the application of thermal imaging of the feet in terms of these three aspects: injury prevention, the analysis of sporting technique and the assessment of footwear and sports equipment.

10.3.1 Injury Prevention

Physical and sporting activity exposes its practitioners to great physical stress, so often producing injuries related to that activity [19, 51, 52]. Injuries are one of the main problems of athletes [48], and it is not only necessary to make a correct and appropriate diagnosis and treatment of injuries, but also to work on prevention, which will allow the sportsman or woman to undertake their sport in greater comfort, well-being and safety [53].

These injuries are accompanied by changes to body temperature. In some cases an increase in temperature (hyperthermia) occurs when there is an inflammation or some other process that leads to an increase in blood circulation, as in infections, tendonitis, bursitis, fractured bones, etc. Whereas a fall in temperature (hypothermia) occurs as a consequence of degenerative processes, a lower vascularization, arterial or venous occlusion, nerve damage, alterations in the autonomous nervous system, etc. [54, 55].

As the human body is bilateral and almost totally symmetrical in terms of its limbs, it may be said that it possesses bilateral symmetry in the surface temperature between two contralateral body zones [56, 57]. The differences of temperature found, therefore, between two opposite zones, called asymmetries, can serve as an indicator of pathologies or dysfunctions [57, 58].

Using this idea, the study of temperature asymmetries through infrared imaging has become a very valid method for use in the prevention, diagnosis and follow-up of an injury [29, 55]. Moreover, this technique allows us to study the temperature of the body surface during and after movement and, therefore, detect the changes produces by exercise [19, 59]. Nevertheless, it must not be used as a diagnosis tool, but as a technique that provides additional information, complementing other tests [31, 48].

According to some studies [60, 61], asymmetries greater than 0.38 ± 0.31 °C in the dorsal region of the foot, and 0.35 ± 0.27 °C on the sole; and 0.40 ± 0.30 °C both in the dorsal and sole, respectively, can be considered abnormal and be associated with an anatomical or physiological dysfunction.

However, a more recent study [57], with improvements both in applying the protocols and in the use of more modern and advanced thermographic cameras, found more accurate asymmetry values: 0.32 ± 0.18 °C for the dorsal region of the foot and 0.28 ± 0.13 °C for the sole; smaller values than those previously accepted for any area of the body in general (0.5 ± 0.3 °C). Moreover, this research recommended avoiding the view of the entire body when undertaking thermal imaging of the feet for specific studies on the asymmetries of the foot because this can reduce the accuracy of the measurement.

One of the factors to which several different injuries are associated, especially in running, are the high plantar loads to which the foot is subject [62]. It has been suggested that the increase in plantar pressures and friction in different regions of the foot may cause raised foot skin temperatures [17, 63, 64]. This supposition is based on the principle of energy conservation, where the mechanic energy produced by the repeated loads that the foot suffers in its interaction with the ground is transformed into thermal or calorific energy [17].

Hence, Shimazaki and Murata [17] found that the regions of the foot with the highest temperatures, the hallux and heel, coincided with the regions of the foot that have the highest contact loads when walking.

On the other hand, the studies of Yavuz and collaborators [64, 65] only reported a moderate lineal relationship between the increase of triaxial plantar loads and the increases of foot temperature as a consequence of walking. They claimed that the changes in foot temperature are produced, not only as a consequence of the plantar load but also blood circulation, the internal load and presence of kinetic friction in the interaction between the foot and the ground.

Another recent study [34] analyzed the relationship between static plantar pressure and the temperature of the feet soles, using thermography, following a 15 min run, with and without footwear. Although no correlations were found between the temperature and plantar pressure in any of the two conditions, they did find higher variations in temperature at the rearfoot in running without footwear, possibly as a consequence of a higher contact load, as the participants ran with a rearfoot striking pattern.

For their part, Taiar et al. [66] found higher increases of temperature in the heel than in the rest of the foot when walking; whereas during running, the temperature of the sole was higher than the complete foot. Thus they claimed that these results were due to the kinematic pattern differences between the two movements, walking vs running, and, therefore, the temperature rises are produced as a result of the specific movement that is undertaken.

To sum up, according to the above mentioned literature, although the evidence is not totally clear and still requires further investigation, it seems that the plantar temperature may be an alternative method for determining the loads or triaxial plantar shearing forces [17, 63, 64]; and, therefore, infrared thermography can provide a useful tool when it comes to assessing the mechanical stress to which the foot is subjected.

Associated with this idea, the authors of this chapter explored, using thermography, the ability of several insoles for reducing contact with ground loads. We analyzed the effect of two types of insoles (prefabricated and custom-made) on the surface temperature of the feet soles, after running, understanding that the use of insoles can reduce plantar pressures in several zones of the foot [67, 68]. Curiously enough, we did not find changes in plantar temperatures (Fig. 10.8), possibly explained by the period of adapting to the insoles where these changes may have taken place.

On the other hand, the study of Wrobel et al. [69] did find lower increases of temperature in diabetic subjects, both on the forefoot and midfoot after walking with an insole created to reduce shearing forces in comparison with a standard insole. In this study, therefore, thermography showed reductions of plantar temperature associated with lower plantar loads.

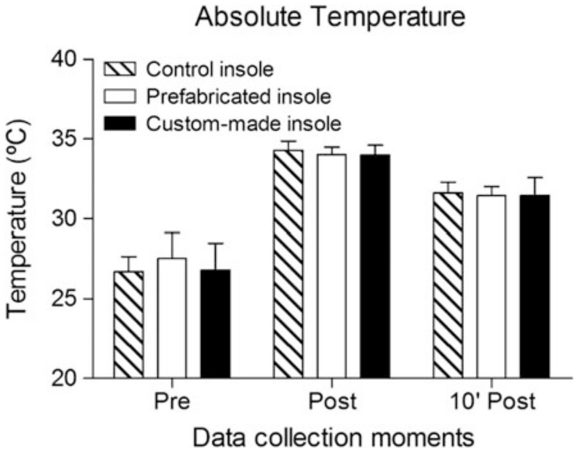


Fig. 10.8 Mean with 95% confidence Interval of the surface temperature of the feet soles at the three moments of measuring (the exercise consisted of a 20 min run)

As the case of Wrobel and collaborators [69] shows, infrared imaging is a very popular tool in the diagnosis and prevention of the diabetic foot [20, 31, 70, 71]. As mentioned before, its usefulness in assessment is evident and, especially, in the prevention of injuries related with physical activity [29, 48, 55], although its application to other injuries of the foot and foot sole, other than that of the diabetic foot, has yet to be fully studied.

To date, injuries related with the feet in which thermography has mostly been used for exploration, for changes in the temperature of the skin, are as follows:

- **Cutaneous injuries**:

When undertaking physical activity, the body is submitted to certain repeated loads that predispose the sportsman or woman to developing an injury. Due to the fact that the skin is the body's first line of defense, it is frequently exposed to the development of dermatological lesions [72]. In the feet, in particular, the friction and repeated pressure of the skin with the footwear or sock during exercise, together with the humidity and ventilation that the foot experiences, often causes traumas to the skin, such as abrasions, chafing, calluses, blisters, black heel or nail disorders [73–75].

Among these lesions, chafing and blisters on the feet and soles are frequent in almost all sports [73, 76]; but they mostly appear in running and especially in long-distance runners [75, 77]. According to a Mailler and Adams' review of dermatological lesions in marathons [77], the most common lesions discovered on the feet were blisters (0.2–39%), followed by chafing (0.4–16%).

Although these lesions seldom hinder the athletes from continuing their activity, they can be very painful, so restricting the normal functioning of the foot and altering the biomechanics of the lower limbs, and, hence, reducing the sporting performance and increasing the risk of injury [73, 78].

During chafing, repeated friction leads to reddening and peeling of the skin [74], whereas during blistering, friction leads to the separation of the layers of the epidermis causing local acute inflammation and the infiltration of liquid into the area [76]. This inflammation can promote an increase in the temperature of the skin, which along with the generation of a point of access, are the main indicators of the formation of blisters on the foot [72, 79]. Thus the studies of Hashmi et al. [72] and Kirkham et al. [80] investigated, using infrared imaging, the thermal changes in the skin of the foot due to friction in order to describe and quantify the physiological responses that take place in the skin of the foot before, during and after the formation of a blister. They arrived at the conclusion that thermal imaging can be of great use in evaluating the scope of the traumatically damaged skin of the foot, both for blisters [72, 81] and other pathologies and injuries whose main characteristic is inflammation and consequently an increase in temperature in the damaged area [82].

Chafing, blisters, calluses, cuts and all types of foot injuries are especially dangerous in people who suffer from diabetes mellitus, given that their complication can lead to the development of an ulcer, which if not treated in time can increase the risk of amputation [71, 82, 83].

Diabetes mellitus is a metabolic disease that is characterized by the presence of hyperglycemia caused by a lack of insulin [54]. It is one of the pandemics of the 21st century and its prevalence is in continuous growth: according to the *International Diabetes Federation* it is estimated that there are around 415 million people suffering from diabetes throughout the world and that this number will increase to more than 642 million in the year 2040 [84].

Among the various complications that this disease brings with it is what is called the diabetic foot, the main cause of which is a reduction in blood supply (vascular disorder) and loss of sensitivity (neuropathy) [70]. These factors, together with the repeated stress that the foot suffers in contact with the ground can lead to the appearance of a diabetic ulcer [85, 86], very common for this disease (it arises in 15–25% of diabetic cases) [87]. Areas with probability of ulceration are associated with local increases in skin temperature due to inflammation and the enzymatic autolysis of the tissue [88, 89]. Thus, checking the diabetic patient's foot temperature is very useful for the early identification of this lesion and would contribute to reducing its incidence [31, 43].

Again, infrared imaging has become one of the methods with the greatest potential for assessing and diagnosing the diabetic foot [20, 70, 71, 90]. Indeed, it is a very popular technique among researchers focusing on the foot and diabetic ulcers. According to several recent studies, it has been proposed as an accurate indicator of diabetes, even better than blood sugar measurements [70], and it seems to be a good substitute for measuring inflammation [82, 85]. Its already mentioned advantages as a non-invasive and non-contact technique, in comparison with other techniques, such as dermal thermometers or liquid crystal thermography [20, 31, 71], benefit the assessment of the diagnosis of the diabetic foot, as it allows us to obtain a full representation of temperature distribution in the plantar and dorsal regions [83], including the medial arch, or of feet with deformities [31]; it creates no undesired pressures or the transmission of pathological organisms [43]; and its high resolution allows the detection of temperature differences, often without the need to apply image processing algorithms [31]. However, it must be stated that its use must always be as a complementary method to other techniques in medical assessment [29, 31].

The study of diabetic foot temperature by thermography has allowed us to relate certain temperatures with the risk of developing complications of the diabetic foot, such as neuropathic ulcer, Charcot anthropathy and other complaints [83, 91]. Here, Sun and collaborators [92] found that diabetic patients in a situation of risk have a significantly higher mean temperature of the foot (30.2 ± 1.3 °C) in comparison with healthy subjects (26.8 ± 1.8 °C). On the other hand, Bagavathiappan et al. [40] found that patients with diabetic neuropathy show a higher mean temperature of the foot (32–35 °C) than patients without neuropathy (27–30 °C).

Similarly, most investigations use asymmetry analyses with thermography by comparing the temperature of the damaged limb with the contralateral limb as control in order to determine the risk of diabetic complication [20, 71, 91]. In particular, van Netten et al. [93] found a difference of temperature of 2.2 °C between two contralateral points as the maximum cut-off value for the detection of these complications. Curiously, this value is the same as that found in previous clinical studies that used cutaneous thermometry [85, 88, 94, 95].

Along these same lines, different authors [41–45] proposed asymmetry analysis on the feet of diabetics by analyzing the differences of temperature between the 4 contralateral angiosomes proposed by Attinger et al. [47], described earlier in Sect. 10.2.4 of this chapter.

Nevertheless, some authors [39, 92] are against diagnosis by asymmetries in systemic diseases that affect both limbs and propose standardizing the absolute temperature of the foot sole with respect to the temperature of the forehead. They take the temperature of the forehead as standard index, given that they claim that this is positively correlated with common central temperatures, is devoid of derivations from thermoregulatory flow and of countercurrent mechanisms that could significantly alter skin temperature [28], and finally because this temperature varies little.

Finally, other studies use more complex methods based on automated detection through the analysis of infrared thermal images, using algorithms, to identify the risk of ulceration [71, 82, 83, 96].

- **Bone injuries**:

The validity of infrared thermal imaging as a diagnostic tool for fractures due to stress has been conclusively shown as a result of the inflammatory process that accompanies them [54]. According to Goodman et al. [97] thermography can provide an accurate and non-invasive way of distinguishing a fracture from stress from other injuries with similar pain symptoms among runners. Besides its application in the follow-up on recovery from the injury, it allows the sportsman/woman to take up his or her activity again in the shortest and safest period of time.

However, its use has been little studied despite the fact that these injuries are produced quite frequently as a consequence of doing sport, especially in the metatarsals [98]. Thus, DiBenedetto [99], in 2002, used thermography to evaluate the risk of suffering a fracture by stress in the foot during basic military training. More recently, Niehof and collaborators [100] reported that this technique can be useful for complementing the diagnosis of complex regional pain syndrome (chronic pain that often compromises a limb, possibly as a consequence of a dysfunction of the nervous system) in patients with fractures in the feet, taking thermographic recordings in the dorsal and plantar regions of the feet.

- **Muscular injuries**:

Muscular injuries, among which are muscle cramps, contractures, strains and contusions are the most frequent injuries among sportsmen/women after osteoarticular injuries [101]. Generally, they have an important inflammatory component that is easily detectable by a local thermal variation [102], so they can be assessed by means of measuring temperature through infrared thermography technique, as several studies have shown [102–105].

The detection of muscular pain from delayed onset muscle soreness (DOMS) has even been investigated with this technique [106]. However, the study of muscular injuries produced in the feet using thermography is still inexistent, when it may be of great interest in such common sporting injuries as plantar fasciitis [53].

We have only been able to find one study [30] concerned with the assessment of muscular injury (low back pain) using thermal imaging on the feet soles. Curiously this investigation found a correlation between temperature changes in the plantar surface of the feet and the intensity of low back pain, due to the fact that the salient innervation of the low back region transports information to the soles of the feet by means of the sympathetic system.

- **Joint injuries**:

Foot sprains usually occur in the midfoot and the first metatarsophalangeal joint, but are not very common amongst sportsmen/women, whereas ankle sprains, closely related with the foot, are among the most common injuries in sport [107, 108].

Even so, there have been few scientific investigations into the application of infrared imaging in the study of any type of ankle joint injury [109] and even less of the foot. According to current literature, Oliveira et al. [109] was the first to use this technique in the assessment of an ankle sprain with the aim of studying its potential as a complementary tool for diagnosing degrees of this injury.

In Fig. 10.9, the image on the right shows an injured foot from judo, with a sprain of the anterior talofibular ligament, and the image on the right the contralateral healthy foot, showing the regions involved in this injury according to Oliveira et al. [109]. Clearly there is a difference of 1.4 °C in temperature in the affected region, the greatest temperature value being found at the uninjured extremity. This is due to the fact that the image of the injury was taken more than 48 h after the injury taking place, so, at that moment, the injury was already in the recovery process. Hence, the inflammatory component, due to the immediate

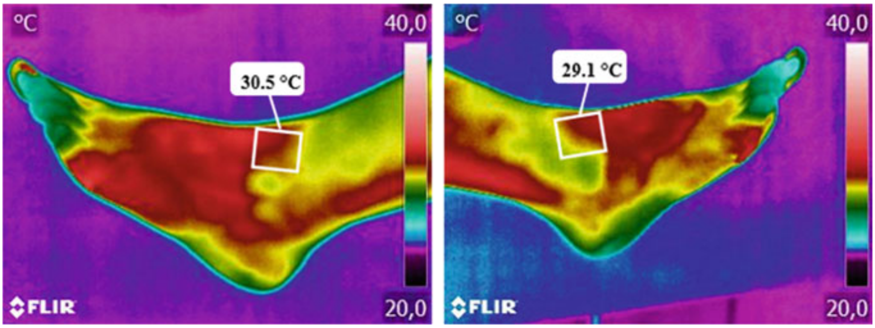


Fig. 10.9 Comparison of asymmetries between the right foot with sprain of the anterior talofibular ligament (*right*) and the healthy left foot (*left*), showing the mean temperature of the affected region

incidence of the injury, had already disappeared, but one can observe a lack of blood flow to the distal zone of the injured foot, associated with a fall in the overall temperature of that extremity, which suggests a hypothermia of the right foot, due to an already known and diagnosed pathology.

Another investigation [110] applied thermography in the assessment of a sprain, this time to the knee, to explore the possible effects of a type of manual therapy in the treatment of a complete rupture of the anterior crossed ligament. Curiously the surface temperature of the skin was measured, both of the knee and the feet and, although no significant changes were found in the temperature of the feet following treatment, it was interesting that the temperature of the feet before treatment was always lower on the injured side in comparison with the healthy side, whereas the temperature in the knee region was always higher on the injured side.

- **Vascular injuries**:

Lastly, hardly related to physical activity and sport, Staffa and collaborators [35] assessed the effect of percutaneous transluminal angioplasty using thermography of the feet and indicated the possibility of using thermal imaging as a means of early detection of the appearance of ischemic disorders of the foot, such as the diabetic foot, previously treated, or the Raynaud phenomenon.

In fact, the Raynaud phenomenon has for a long time been evaluated using infrared thermography [111–115], being especially focused on the hands [116, 117].

It is characterized by the manifestation of episodic vasospasms in the fingers and toes as a consequence of exposure to cold temperatures or strong emotions [118]. During these vascular spasms a narrowing of the blood vessels takes place which reduces the blood supply to the fingers and toes and produces a drastic reduction in temperature [113, 118].

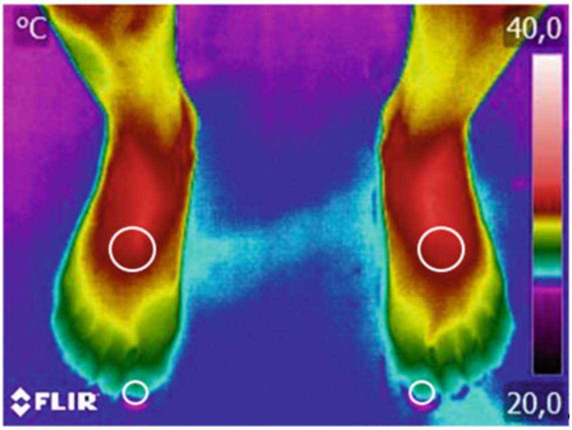
Specifically, the study of Lim et al. [117] identified, through measuring the gradient of foot temperature using infrared thermography, a difference of temperature equal to or greater than 3.11 °C between the dorsal of the foot and the big toe, as the cut-off value that may indicate the presence of this disease (Fig. 10.10)

Both Lim et al. [117] and Tse et al. [115] reported that this technique can be very useful in diagnosing this phenomenon in the foot. Indeed, Tse et al. [115] claim that infrared thermography provides a more accurate and objective method than traditional physical exploration undertaken by health professionals by identifying the asymmetries of skin temperature related with the Raynaud phenomenon.

10.3.2 Determining the Pattern of Running

Sporting specialization can affect the normal thermal patterns in healthy athletes [119], causing thermal asymmetries that are specific to a particular sport, such as the forearm in tennis players, the tibialis anterior in football players, the arm in

Fig. 10.10 Adaptation of the method used by Lim et al. [117] for measuring temperature gradients, comparing the dorsal of the foot with the big toe



volleyball and basketball players or the grasping forearm of a judo practitioner [54]. It is, therefore, important to know the thermal pattern commonly presented by the participants of a sport and the individual thermal patterns of the sportsman or woman in particular, before assessing the thermal asymmetries and venturing a possible injury [54].

Likewise, the execution of a sports technique, depending on the sport and the characteristics of the individual, can present certain thermal patterns, so it may be suggested that infrared thermography can be of great use to coaches, providing them with valuable information on the muscular activity undertaken and the technique employed as well as contributing to their improvement in training [120].

With this idea, and in relation with the foot region, the authors of this chapter undertook a preliminary study, the aim of which was to analyze the relationship between the temperature of the skin surface on the foot sole and the eversion of the ankle in running in order to determine whether infrared thermography could be a quick and simple tool for predicting the degree of ankle eversion in runners [121].

As Fig. 10.11 shows, there is a positive correlation between the symmetries of temperature variation (temperature difference between the medial side and the lateral side of the foot as a result of running) and the maximum ankle eversion during stance phase (MAE), but not with the eversion in first contact of the foot with the ground. So, finally it was concluded that in neutral pronator runners (with maximum eversion values of between 7 and 15°) the higher the temperatures observed in the internal region of the foot, the greater the degree of eversion.

Hence, it was suggested that thermography has great potential for predicting the foot type contact during running (pronation-supination), although further research is required to evaluate runners with different support patterns so as to be able to corroborate the findings.

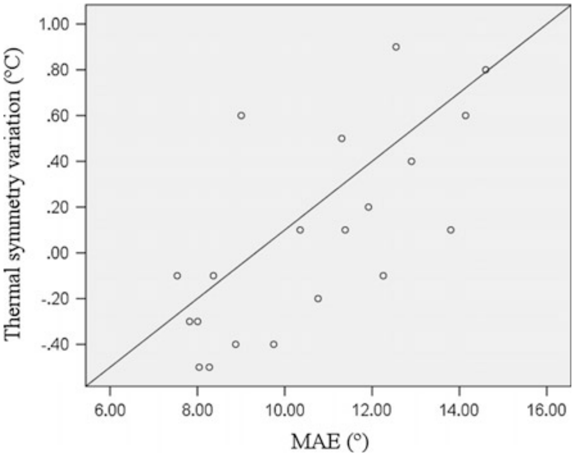


Fig. 10.11 Correlation between the maximum ankle eversion during stance phase (MAE) and the variation of the thermal symmetry of the plantar temperature (difference in temperature variation due to running between the medial and lateral sides of the foot) r = 0.7, $p = 0.001$

Along the same lines, the following image (Fig. 10.12) suggests that both the type of running contact (pronation-supination) and the running foot strike pattern of an athlete (forefoot, midfoot and rearfoot) could be studied by evaluating the temperatures of the soles of the trainers following exercise, simply by taking thermographic images.

This idea lacks scientific evidence, as there is no literature on it. Similarly research using thermography in other subjects that could also be interesting for the evaluation of this technique, such as the study of lateral dominance, the use of one extremity more than another, or the greater application of load on one foot rather than the other, and not only in running, but also in any sport where the foot comes into contact with the ground.

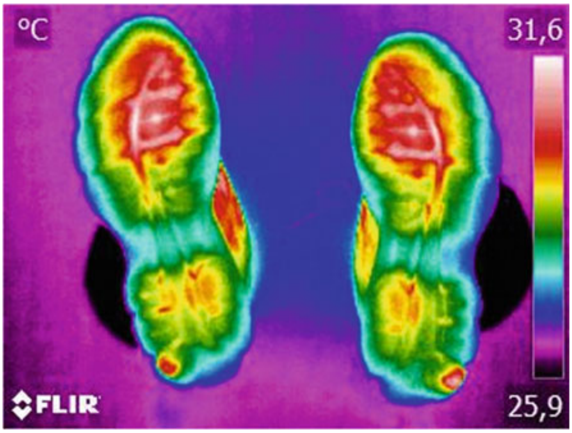


Fig. 10.12 Thermographic image of the soles of an athlete's footwear 10 min after running that could predict the type of foot contact (pronation-supination) due to the differences in temperature between regions

10.3.3 Determining the Effect of Footwear and Textiles on the Foot

Sports equipment significantly influences the sporting performance of the athlete in terms of the possible development or prevention of an injury [50, 122]. Specifically, the sports shoe plays an important role in these two aspects in a great number of sports where the interaction of the foot and the ground predominates.

Currently the sports market offers a huge selection when it comes to choosing specific footwear as there are many types of wide ranging characteristics that differ both in structure and functionality, and in style [123]. Hence, the sportsman or woman must choose footwear bearing in mind the architecture of their feet, their sport mechanics and the specific demands of their sports modality, as those characteristics will reduce the risk of injury and increase performance [124].

Moreover, thermal comfort is another characteristic that has to be taken into account in the design and choice of footwear, as it has great repercussions on general comfort while exercise is being undertaken and is also associated with improvement in sporting performance [125–127]. The thermal properties related with thermoregulation and thermal comfort are breathability and thermal insulation [125, 126]. Consequently, footwear that allows good breathability during exercise or that in very cold situations and adverse climatology are insulating and impermeable will favor the thermal comfort of the athlete [49, 125].

Another garment that has an influence on the microclimate created inside the shoe and directly affects the thermoregulation of the foot during sport is the sock. However, there are very few studies on the effect of socks, despite the fact that new textiles and fabrics have been designed to improve thermal equilibrium and to provide greater thermal comfort to the user [128].

In this sense, thermographic information on the foot can be very useful for the functional design of both footwear and socks; for the evaluation of the thermal properties that these garments offer to sportsmen and women, and also for observing the thermoregulation of the foot depending on the type of shoe or sock in the sports context [129].

In fact, according to the review published by Banerjee et al. [130], various applications of infrared thermography have already been reported in the textile industry, such as measuring the thermal properties of textile materials, measuring dryness and the transport of heat and humidity, analyzing the mechanical properties or the comfort of the garment, where this technique can play a crucial role in the future.

- **Breathability and sweat**:

As mentioned previously, the foot functions as a thermal radiator, of great importance to human thermoregulation. So, when the feet are inside footwear for long periods of time, the temperature and humidity within the footwear tends to increase [17], and can begin to cause discomfort and irritation and even provoke the development of an lesion or bacterial infection. This fact is especially so in summer and in warm and humid regions, as Kinoshita and Bates found in their study [131], temperatures on the sole of the footwear greater than 50 °C being recorded during a 40 min run on a summer's day.

The zones that are furthest away from the opening of the shoe and sock, i.e., the toes, receive less air movement (less ventilation), so their temperature will be highest [128].

These high foot and footwear temperatures, together with restrictions to ventilation as a consequence of the closed shoe, cause a high production of sweat by the foot aimed at trying to maintain body temperature around 37 °C [128].

It has been shown that the foot produces great amounts of sweat in comparison to the rest of the body [132], as it has a dense region of eccrine sweat glands. These glands are distributed all over the body, but are mostly concentrated on the palms of the hand, feet soles and forehead. They possess an innervation of the sympathetic nervous system and their secretion is commonly called sweat, so contributing to heat loss through evaporation [17]. Sometimes the feet and footwear produce bad smells due to the proliferation of bacteria resulting from excessive humidity derived from sweat in that area.

Nevertheless, in a study the aim of which was to describe the production of foot sweat during exercise, in this case running, a greater amount of sweat secretion was observed in the dorsal of the foot than in the plantar zone [133], even when there is a higher number of sweat glands in feet soles [2]. Moreover, it was also found that the use of footwear limits the increase in sweat production as running intensity increases [133].

Thus a particularly important factor both for the comfort of sportsmen and women's feet and for the appropriate maintenance of heat dynamics during exercise is that the footwear or sock presents suitable properties of heat dissipation through convection and conduction currents between the feet and the fabric and improves breathability, i.e., the elimination of sweat through evaporation [14, 123]. For its part, the sock is fundamental for maintaining the climate of the foot, given that it transports the sweat from the foot to the upper part of the shoe so that it evaporates better [123].

Thermal analysis of the sports shoe using infrared thermal imaging can, therefore, be very useful in identifying the areas that provide the greatest breathability to the athlete and help him or her to choose the footwear that facilitates thermoregulation, as shown in Fig. 10.13.

As can be seen in the next figure (Fig. 10.13), the specific running shoe presents higher temperatures to that of the mountain shoe. This is due to the fact that the running shoe is more breathable and less insulated, so facilitating the flow of temperature from the foot to the outside of the shoe. This method of analyzing footwear could become a very interesting field of research. As can be observed, the terms insulation and breathability are closely linked, so the characteristic of insulation will now be explained.

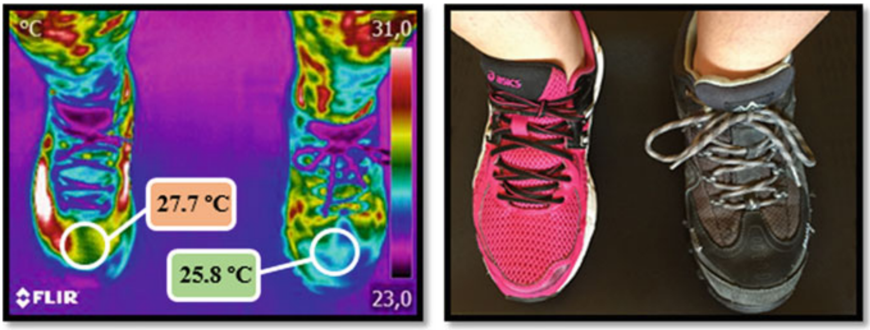


Fig. 10.13 Thermographic images of the dorsal views of the feet with two different sports shoe after undertaking a 10 min run: a specific running sports shoe (*left*): and a trail sports shoe (*right*). Mean temperatures of the regions within the circumferences are shown

- **Insulation**:

During exercise the feet remain hot. However, during inactivity the temperature of the feet falls rapidly [49]. One of the properties of footwear that helps to reduce heat loss is thermal insulation, the importance of which is accentuated when physical activity is undertaken at low temperatures or in cold and humid regions [134].

Insulation can be increased through garments or materials added to the footwear that provide local insulation, such as on the toes and heels, whose effects are clearly notable on the mean temperatures of the skin [49]. However, wearing a thick pair of socks in a tight shoe can produce the opposite effect, increasing the accumulation of humidity and so reducing the insulation of the footwear by up to 45% [134, 135].

The thermal insulation of footwear and socks can be assessed through two methodologies: directly on the feet of human beings [136], or using a thermal foot model [49, 137]. The main drawback of which is that it cannot contemplate the conditions and changes that are produced during a specific sports practice, and the alterations caused in the physiology of the foot of the user as a consequence of that practice.

To date, there have been two investigations carried out on human beings that have reported increases in temperature in certain regions of the foot, during walking and running, probably as a result of the effect of footwear insulation [17, 34], respectively.

The latter, of Priego Quesada et al. [34], used, as the skin measuring technique, infrared thermography, the main advantage of which is that it does not interfere in the behavior of the athlete when in use, nor does it effect the thermoregulation of the foot as it is non-invasive. Other methods can be invasive, such as incorporating sensors on the surface of the skin of the foot, which was used by Shimazaki and Murata [17]. However, the main drawback of the infrared thermography method is that the measurements have to be taken in static positions and without footwear and socks, as it is not possible to undertake then while running in a real situation. In this sense, surface sensors have a clear advantage.

On the other hand, in various studies the aim of which was to compare foot temperature with the use of different models of footwear and socks during running, the conclusion was reached that the perception of foot temperature by the user may differ from the real physiological temperature of the foot [123, 128]. Thus, it may be said that, when determining how a shoe or sock affects the physiological temperature of the foot, the study has to be undertaken through techniques that provide more precise information than the subjective perception of the user. Infrared thermography does this, providing speed and simplicity to the assessment. We cannot, however, ignore the perceptions of the user, given that they will be the ones to determine thermal comfort and, consequently, the performance of the athlete [128].

10.4 Conclusions

As explained in this chapter, the thermographic analysis of the foot in sport sciences presents numerous and interesting applications. These applications range from the prevention of injuries and the analysis of the effects of sporting technique on foot temperature to the evaluation of sports equipment (footwear, insoles and socks). Infrared thermography, therefore, can provide vital information for the athlete on how to improve his or her performance and on reducing the possibilities of injury. Nevertheless, evidence is scarce in these fields and future studies are required to analyze the hypothetical potential of infrared thermography dealt with in this chapter. Methodologically, there are also issues that need to be addressed. An analysis needs to be made of which determination of the regions of interest on the foot can be of assistance to each of the different applications. Moreover, studying the reproducibility of the foot temperature variation as a result of exercise is an aspect that must be investigated. In conclusion, thermography in the analysis of the foot in sport sciences presents great potential, although there is at present little literature that has gone into any depth on those applications.

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Chapter 11
The Application of Infrared Thermography in Equestrian Sport

Maria Soroko, Mina C.G. Davies Morel and Kevin Howell

Abstract Infrared thermography has found a broad range of applications in equestrian sport as a complementary diagnostic tool in veterinary practice and sport performance. Thermal imaging is useful for monitoring changes to a horse's body surface temperature resulting from exercise, allowing evaluation of the contribution of individual parts of the body to horse performance. Thermography can play an important role in rehabilitation, indicating an area of abnormality and so guiding where to concentrate further diagnostic imaging or treatment.

11.1 Introduction: Detection of the Body Surface Temperature of the Horse and the Influence of the Environment on Temperature Changes

Equine sport is a unique discipline that involves two athletes, horse and human, working together as a team. Equine sport has two main sectors: racing and equestrianism. Horse racing is an immensely popular global sport divided into flat and

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jump racing (also referred to as National Hunt racing). In Great Britain, professional horse racing is conducted on 59 racecourses. Each racecourse is responsible for an average of 10 race meetings per annum [1].

Equestrianism involves jumping, dressage, eventing, driving, endurance, vaulting and reining disciplines. With more than 15,000 events each year, Europe is the location of more than 70% of the equestrian events held worldwide. The International Equestrian Federation (FEI) promotes equestrianism in all its forms and encourages the development of equestrian competitions throughout the world. Animal welfare, respect and health are the core values of the FEI.

Sport horses are particularly susceptible to injuries due to the high physical demand of the sport, but also due to genetic predispositions, age, conformation of the horse, type of training, riders skills, quality of surface or previous injures [2, 3]. The contribution of each of these factors to possible injury development needs to be separately established to obtain better knowledge of injury risk and the ways to protect horses from training lost. Horses health and welfare is under human control, therefore increased knowledge in this area should bring about a decrease in early retirement of animals from sport performance [4]. For the improvement of the horse's health and welfare, it is important to have a tool which can predict future abnormal conditions or help in rehabilitation programmes.

Equine thermography has been established as a complementary diagnostic tool, which can detect an area of changed body surface temperature because of injury (Fig. 11.1). The broad application of thermography in veterinary medicine, rehabilitation and in assessment of welfare has been found to be very useful by many authors.

11.1.1 Normal Body Surface Temperature Distribution of the Horse

A constant temperature is a distinct feature of warm-blooded animals. To maintain it, heat generation and dissipation must balance within the body. An adult horse is assumed to have a rectal temperature from 37.2 to 38.1 °C. A thermoregulatory centre located in the hypothalamus is responsible for maintaining a constant temperature by responding to incoming thermal information and determining how much heat is to be dissipated at any moment to maintain an optimum environment for all the cells of the body. Heat is produced as a result of chemical thermogenesis, taking place by tissue oxidation.

When a horse is at rest, its muscles produce approximately 50 kcal/min of heat, which is sufficient to maintain a proper internal body temperature [5]. During exercise, approximately 70–80% of the energy produced by working muscles is released as heat, and the amount of heat generated rapidly increases with work rate. A horse in trot generates 100 kcal/min, while in gallop this increases to 300 kcal/min. The heat produced during exercise increases the temperature of the circulating blood. Blood flow increases in capillaries under the skin, where heat

Fig. 11.1 Thermographic measurement with a hand held camera of the horse's limb

dissipation takes place from the skin surface. Compared to humans, muscle makes up a much larger proportion of the total body mass in the horse. Therefore, heat produced by muscle during exercise by a horse must be lost to the environment very effectively.

Heat is dissipated at the skin surface mainly through convection, perspiration (evaporation) and infrared radiation. Evaporation is due to the molecular pressure difference of water vapour between the skin surface and environment, while the other components arise from the temperature difference between the skin surface and the environment [6]. The exact contribution of these processes during exercise is not fully understood: the balance of heat dissipation, transmission and storage may change in response to training time, gait type and speed, as well as a changing external environment. Research shows that the blood flow through the skin and evaporation are the key factors in the rate at which heat is dissipated to the environment [7]. Other factors influencing the rate at which excess heat is eliminated are the horse's body surface area, hair coat thickness, the temperature and humidity of the external environment, and wind speed.

An understanding of normal body surface temperature distribution is essential in detecting any abnormal pathologies [8, 9]. The distribution of body surface temperature across a horse is marked by a considerable inter-individual variability and is affected by environmental conditions [10, 11]. In the study by Soroko et al. [12] correlation between skin and ambient temperature was high ($r > 0.85$ at all skin sites). The variability of the temperature distribution in response to a changing ambient temperature has also been investigated. Mogg and Pollitt [13] found that low ambient temperatures (below 15 °C) caused vasoconstriction and Palmer [10, 14] similarly reported that temperatures below 12 °C resulted in decreased blood circulation, leading to reduction in body surface temperature in the distal parts of limbs. Ambient temperatures of 18–20 °C caused an increased, but unevenly distributed, blood flow arising from vasodilation in the distal limbs [13].

Thermographic patterns of the healthy horse have been described [8, 15–17], with a high degree of symmetry between left and right sides of the body [10]. The distribution of skin surface temperature depends, in part, on thermal conduction from the veins lying at various depths within the body tissues [18–20]. Heat emanating from deeper lying arteries and internal organs is additionally conducted by the subcutaneous tissues. The distribution of the body surface temperature is determined by the arrangement and volume of the subcutaneous layer, the temperature of which depends on the metabolic activity of muscles. Body areas containing richly vascularised muscle tissue (e.g. neck, back, croup and chest) have higher surface temperatures in comparison to body areas where less muscle develops (e.g. proximal forelimb and hindlimb) or where they are not found at all (e.g. distal parts of the forelimbs and hindlimbs) (Fig. 11.2).

The horse's hair coat absorbs infrared radiation emitted from the skin surface [21]. Air retained in the hair coat is a poor thermal conductor, affording efficient insulation against excessive heat loss from the skin [16]. Therefore, the hair thickness, density, length and arrangement also contribute significantly to the surface temperature distribution [22, 23]. The effect of the hair coat on thermal emission has many considerations. The animal's coat, as seen in a thermographic image, is simply the surface of a material with complex underlying layers. Its equilibrium temperature is determined by the balance between the loss of heat by convection to the surrounding air, heat conduction from the skin surface through the coat, and also by the exchange of thermal infrared radiation to and from the environment [24]. The efficiency of infrared radiation from the coat surface is determined by the emissivity of the material. Whilst the emissivity of the hair coat is high, it will not be precisely known for each animal, and may vary across the surface, thus limiting the accuracy of temperature readings attained from thermographic imaging.

Clark and Cena [23] described the transmission of thermal radiation through animal coats of various colours and the related effects of environmental factors. The influence of radiant solar energy on pigmented and non-pigmented areas of the coat was also examined. There was a significant difference in body surface temperature (up to 8 °C) between hotter black pigments compared to white. It was concluded that body surface temperature differences are clearly expressed on the thermal

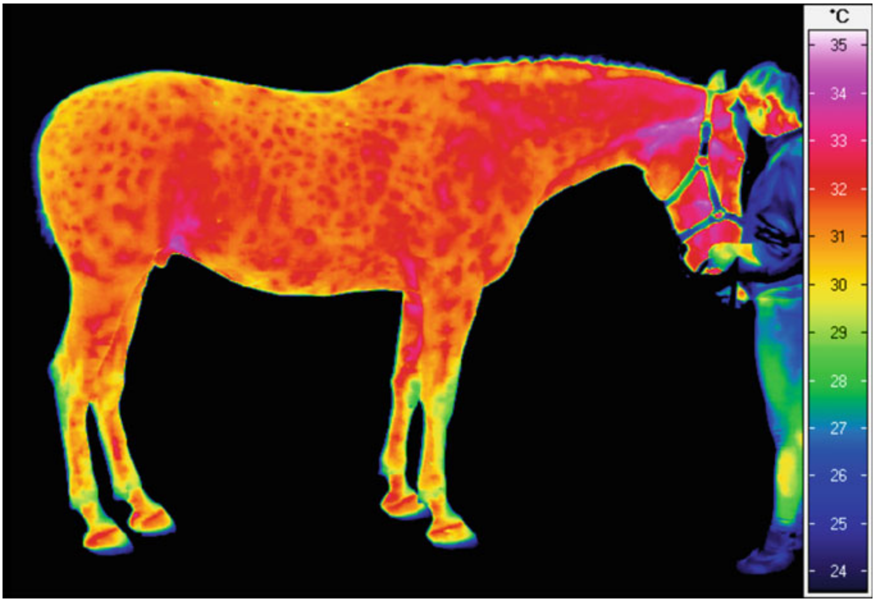

Fig. 11.2 Thermogram of the right lateral aspect of a horse. The warmest areas of the body are presented in *red*, *yellow* and *green* colours represent cooler areas, and *blue* colours represent the coldest areas of the body

image, but environmental factors affect the reliability of thermography for animal temperature measurements. In a later study, it was confirmed that under direct sun exposure, black areas of the skin are significantly warmer compared to unpigmented body areas. However, indoor examination did not give rise to a significant difference between pigmented and non-pigmented areas [14]. It was also suggested that solar energy absorption depended on the shape and position of areas in relation to the sun [22]. Accuracy can also be influenced by curvature of the surface and variations in coat thickness [23, 25]. Turner et al. [25] investigated the influence of coat clipping on body surface temperature changes, demonstrating that clipped areas were warmer than unclipped areas. After exercise both clipped and unclipped areas of the limbs showed similar increases in temperature, indicating that clipping was not necessary to obtain reliable thermographic results.

Based on the above findings some generalisations can be made regarding the normal thermal pattern of the horse. Most studies report that the chest, and the area between the hindlimbs along the ventral midline are the warmest and the back and distal parts of the limbs are the coolest areas of the body [16, 26]. More detailed work by Tunley and Henson [8] indicated that the dorsal midline along the back was 3 °C warmer compared to either side of the midline symmetrically, in both trained and untrained horses. Similar results were found in another study, where the back was warmer than the sides of the horse by 2 °C [27]. The temperature of the warmest areas of the distal parts of the forelimbs (the metacarpus bones, the fetlock

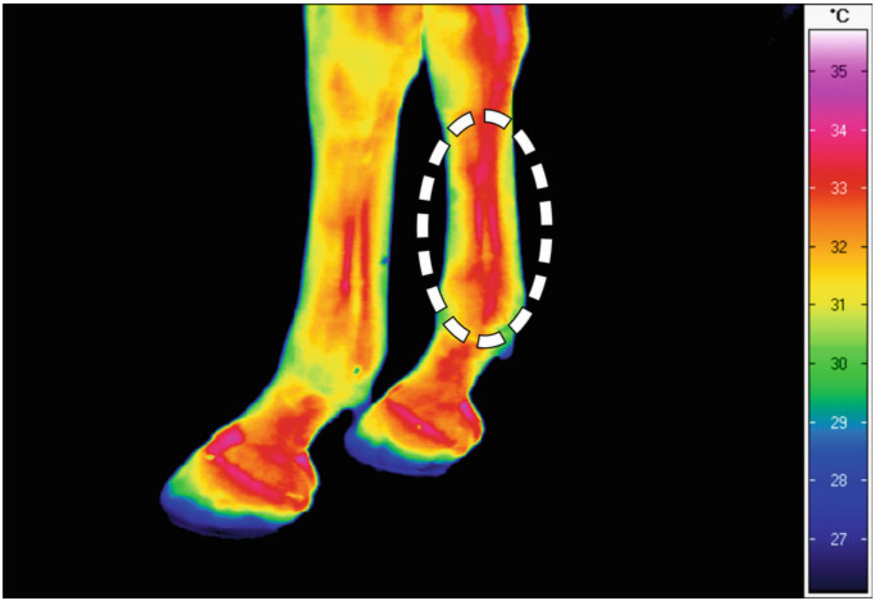

Fig. 11.3 Thermogram of the distal forelimbs (*left* lateral and *right* medial aspects) from the *left* side of the horse, illustrating the higher body surface temperature associated with blood vessels (palmar artery and vein and digital artery indicated by dashed circle)

and pastern joints) is influenced by the vascular supply. Hence the main blood vessel areas—the palmar and digital arteries, and the palmar veins from the lateral and medial aspects—appear the warmest (Fig. 11.3). Similarly in the distal hindlimbs the warmest areas (the metatarsus bones, and the fetlock and pastern joints) are along the plantar and digital arteries, and also the plantar veins from the lateral and medial aspects (Fig. 11.4). The dorsal (cranial) and palmar/plantar aspects of the limbs are relatively cool as they are situated away from major blood vessels. The highest distal limb temperature viewed from the dorsal aspect is found in the coronary band, as it is situated close to the major arterio-venous plexus [9, 28] (Fig. 11.5). When viewed from the palmar/plantar aspect, the highest temperature is at the area between the heel bulbs (Fig. 11.6).

Although the body surface temperature patterns in different horses are similar, no two horses are found to have an identical body surface temperature. The temperature distribution is affected by anatomy, individual traits in performance of the horse, injuries, training type and the level of animal adaptation to stress loads [9, 29]. It has been suggested that values of surface temperature across an individual healthy horse can range from 19 °C up to 32 °C. Flores [30] found the highest body surface temperatures (27–32 °C) on the head, neck, shoulder and flank and the lowest temperatures (24–26 °C) on the distal limbs. However, other studies have indicated slightly different temperature ranges, with the highest temperatures (25–28 °C) in the area of the head, middle part of the neck, chest and flanks, and the

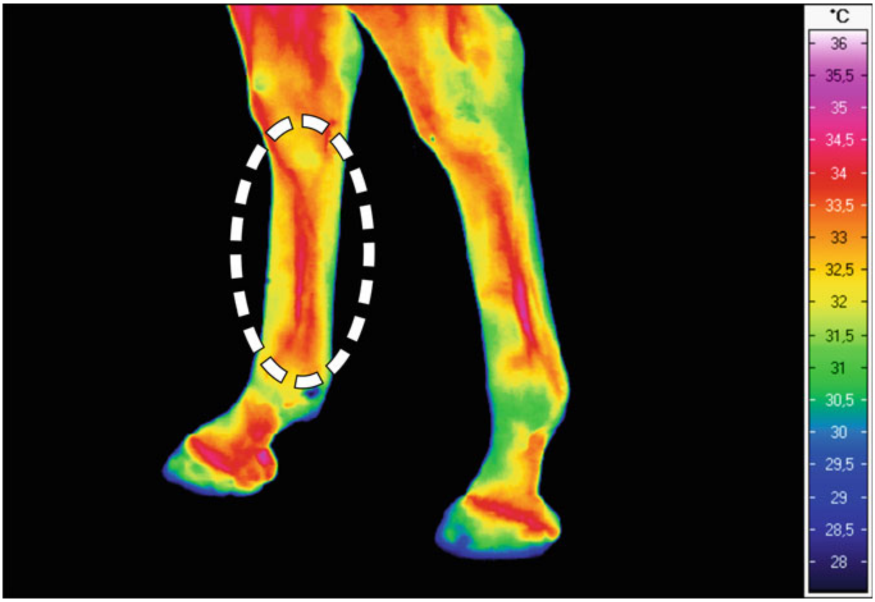

Fig. 11.4 Thermogram of the distal hindlimbs (*left* lateral and *right* medial aspects) from the left side of the horse, illustrating the higher body surface temperature associated with blood vessels (plantar artery and veins and digital arteries, indicated with dashed circle)

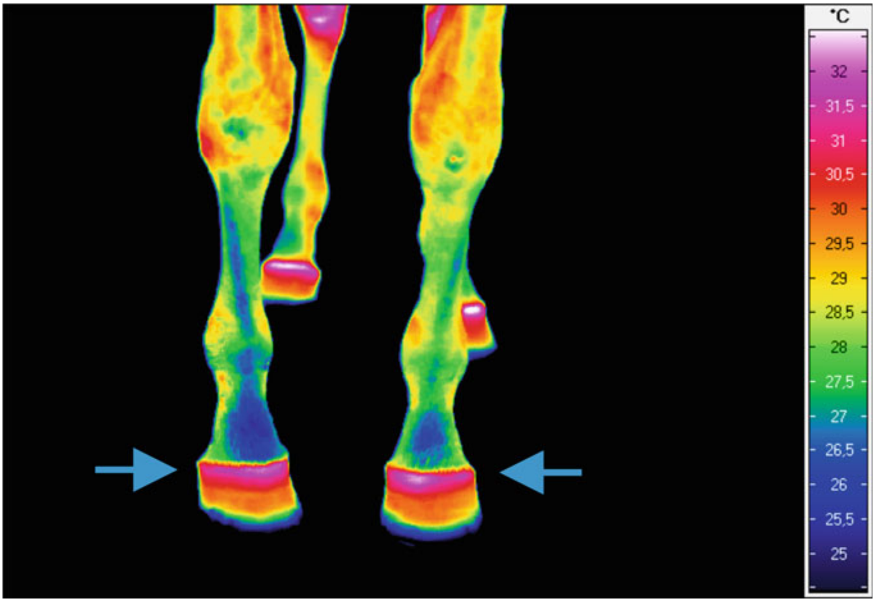

Fig. 11.5 Thermogram of the distal *right* and *left* forelimbs from the dorsal aspect, illustrating the higher body surface temperature in coronary band (indicated by arrow)

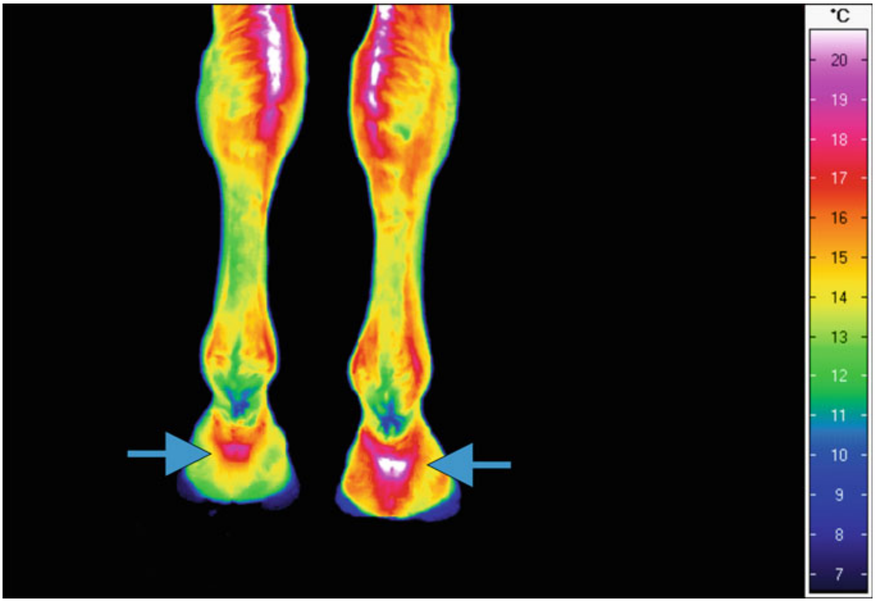

Fig. 11.6 Thermogram of the distal *left* and *right* forelimbs from the palmar aspect area between the heel bulbs illustrating the higher body surface temperature in area between the heel bulbs (indicated by arrow)

lowest temperatures (19–23 °C) at the distal limbs [26]. The differences in temperature ranges between these can probably be explained by different ambient temperatures to which the horses were exposed.

11.1.2 Recommended Procedures for Equine Thermographic Examination in Accordance with Standards for Thermal Imaging in Veterinary Medicine

The proper use of thermography to evaluate body surface thermal patterns requires a controlled environment, and the physiological state of the horse must be considered in order to reduce variability and eliminate errors of interpretation [31]. Thermography measurement standards have been established in equine veterinary medicine [32, 33]. The thermographic examination should be performed in an area sheltered from the sunlight, in the absence of air drafts and extreme variations in ambient temperature [9, 14, 34]. The temperature of the examination area should ideally be maintained between 21 and 26 °C. This is particularly important for the determination of body surface temperature of the distal parts of limbs, which are particularly unstable at low ambient temperatures due to vasomotor activity [13].

At low temperatures there is also a statistically significant influence on the bilateral symmetry of distal limb surface temperature [10]. It is recommended that the horse should be acclimatised in the examination room for 15–20 min prior to imaging. A longer period of equilibration, up to 60 min, may be required when the examined animal is transported from an extreme cold or hot environment [8, 10].

The thermographic examination should be performed when the horse is at rest, before exercise [33]. The horse must have a clean, dry hair coat and skin and should be groomed at least one hour before the examination. Artifacts can be produced by any material on the body surface such as water (wet areas), dirt, thickened coat, irregular patterns of clipping or scars [14, 35, 36]. It is necessary that the hair coat be short, of uniform length, and lay flat against the skin to permit thermal conduction [25]. The feet should be clean, picked out and brushed to remove external contamination. Anti–inflammatory medications, vasoactive drugs, regional and local nerve blocks, sedation and tranquilisation should be avoided where possible because of their effect on superficial blood perfusion [33]. Blankets and bandages should be removed at least 30 min before examination [14].

Biological materials such as skin and hair coat have generally high emissivity, making these surfaces efficient infrared radiators. In equine thermography, a lack of accurate knowledge about the emissivity of the surfaces of the horse may limit the accuracy of temperature measurement. Emissivity is usually assumed to be 1.0, which will have a small impact on accuracy of perhaps a few tenths of a degree Celsius [35].

For thermographic examination the horse should be presented with forelimbs and hindlimbs equally loaded and the lateral and medial aspects of the distal parts of the limbs visible from both sides [37]. Imaging of the horse should include a lateral aspect of the whole body from both sides. The distance between horse and camera should be about 7 m. Images of the distal parts of the forelimbs and hindlimbs should include dorsal, palmar/plantar, lateral and medial aspects. The distance between camera and horse should be set at 1.5–2 m [38]. The thermograms should also include the lateral upper part of the thoracic and pelvic areas, and also the lateral aspect of the neck, head and trunk from both aspects. The distance between camera and horse for these parts of the body should be about 3 m. The thoracolumbar region of the spine should be imaged from the dorsal aspect [27] from a height of approximately 2 m and at a distance of 1.5 m from behind the horse. Close up thermographic images of regions of interest can be taken if necessary. Analysis of body surface temperature symmetry across contralateral body areas can be performed.

11.2 Application of Thermography as a Complementary Diagnostic Tool in Veterinary Medicine

Thermography was first introduced to veterinary medicine in the mid-1960s, when several papers reported the potential value of thermography in diagnosis. A key study presented applications of thermography for the detection of splints, bruised joints and bowed tendons [39]. Delahanty and Georgi [40] introduced the use of thermography in detecting clinical cases of squamous cell carcinoma, slab fractures of the 3rd metacarpal bone, bone spavins and deep cervical abscesses. Since then, thermography has evolved steadily to be employed in a variety of areas in equine medicine.

11.2.1 Thermographic Diagnosis of Soft Tissue Injury and Superficial Bone Lesions in Equine Medicine

Strömberg [36, 41, 42] was the first to use thermography in detecting and monitoring orthopedic injuries of the distal parts of the limbs in racehorses. These studies reported that the thermographic image can predict inflammation of the superficial digital flexor tendon up to 14 days before clinical signs appear. Thermographic examination detected the increased temperature of the injured limb, even though radiography did not show any changes. It was concluded that thermography can play an essential role in preventing lameness in racehorses.

Further studies investigated the use of thermography in diagnosing pathological conditions of the limbs and back [15, 43–46]. Clinical diseases of the distal parts of the limbs that have been recognised and characterised by thermography include tendinopathy (Fig. 11.7), laminitis [9, 16], joint arthritis (Fig. 11.8) [17, 43],

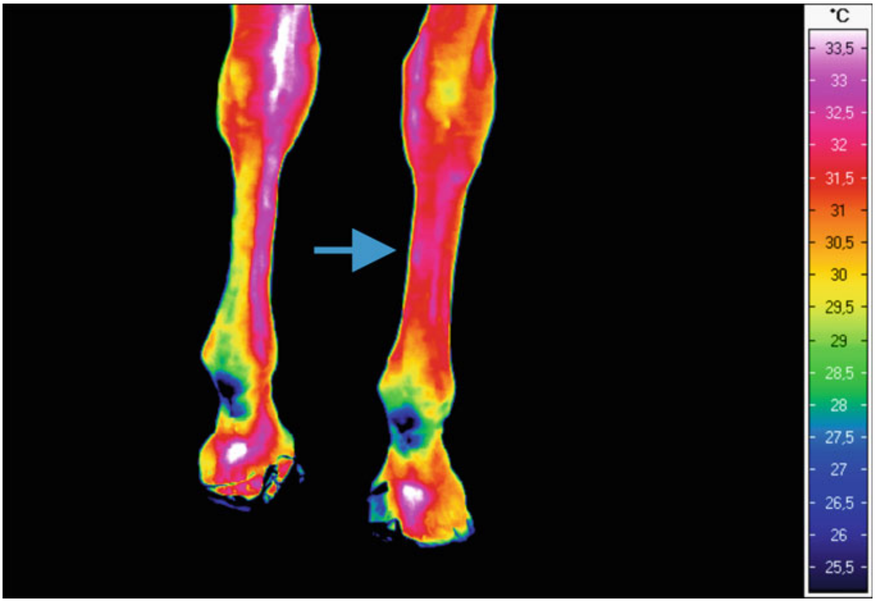

Fig. 11.7 Thermogram of the palmar aspect of the distal part of the forelimbs, illustrating tendinopathy of the superficial digital flexor tendon at the level of 3rd metacarpal bone of the *right* forelimb (indicated by arrow)

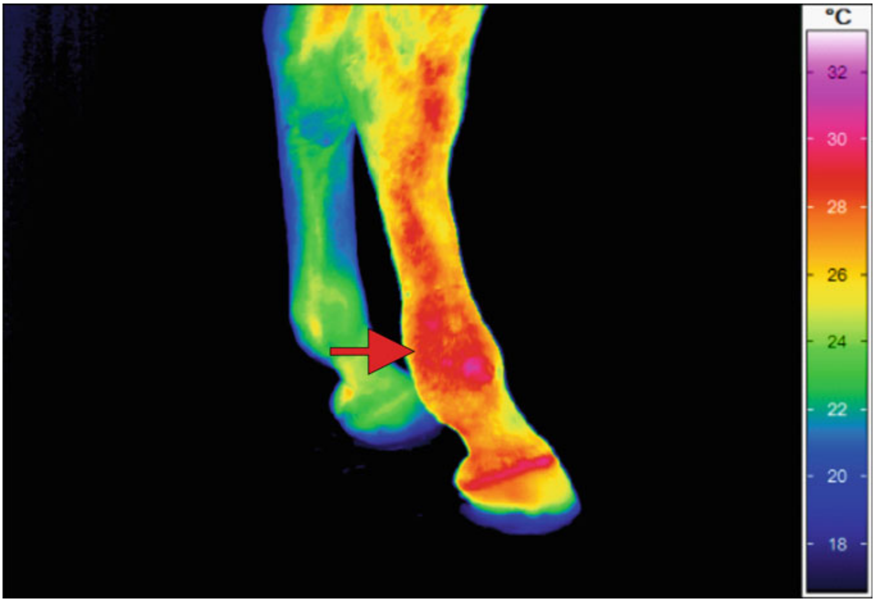

Fig. 11.8 Thermogram of the distal part of the *right* and *left* hindlimbs (lateral and medial aspects respectively), illustrating fetlock joint arthritis of the right hindlimb (indicated by arrow)

suspensory desmitis [16], inflammation of the stifle [47], stress fractures [16], bucked shins (Fig. 11.9) [44], sole abscesses (Fig. 11.10), and navicular syndrome [25].

For back abnormalities, thermography is useful in localising spine-related diseases associated with subluxation of the third lumbar vertebrae [15], neuromuscular disease of the thoracolumbar region [27], inflammation of spinous processes (Fig. 11.11) [46] and intervertebral arthritis of the thoracolumbar spine [48, 49].

11.2.2 Thermography Complementary to Ultrasonographic and Radiographic Examinations

Thermography examination provides injury localisation and physiological inflammation information about the affected tissue. However, it is unable to specify the injury and cannot define the lesion etiology. Therefore the value of thermography in veterinary medicine is greatest when it is used complementary to other modalities. Much research emphasises the importance of the application of thermography as complementary to ultrasonographic and radiographic examinations in the evaluation of soft tissue injury and superficial bone lesions [9, 48, 50]. Vaden et al. [17] have shown the value of combined thermographic and radiographic examination in joint arthritis. Their study was based on 20 racehorses clinically evaluated for abnormalities in their gait due to pain in the tarsal joint. The examined horses were

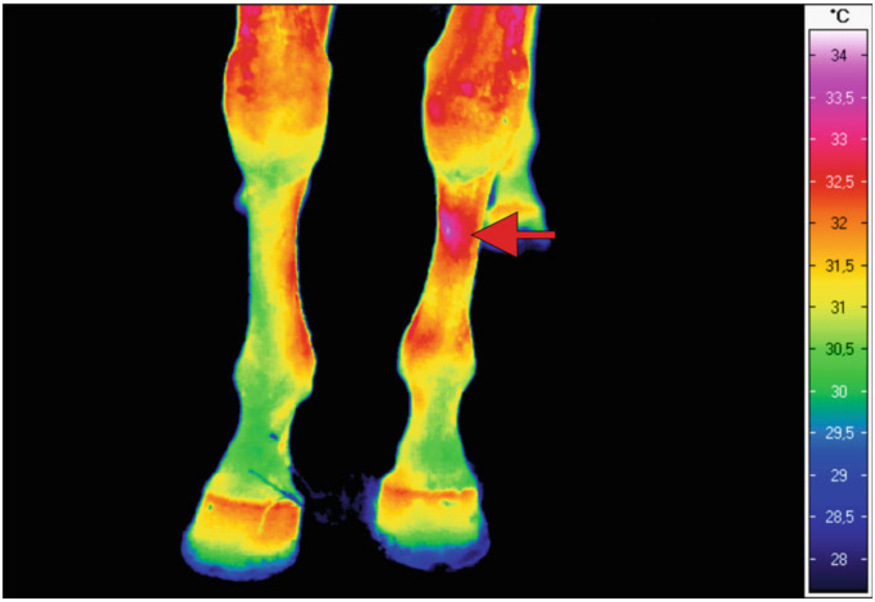

Fig. 11.9 Thermogram of the distal part of the *right* and *left* forelimbs (dorsal aspect), illustrating clinical inflammation of the left 3rd metacarpal bone (bucked shins) (indicated by arrow)

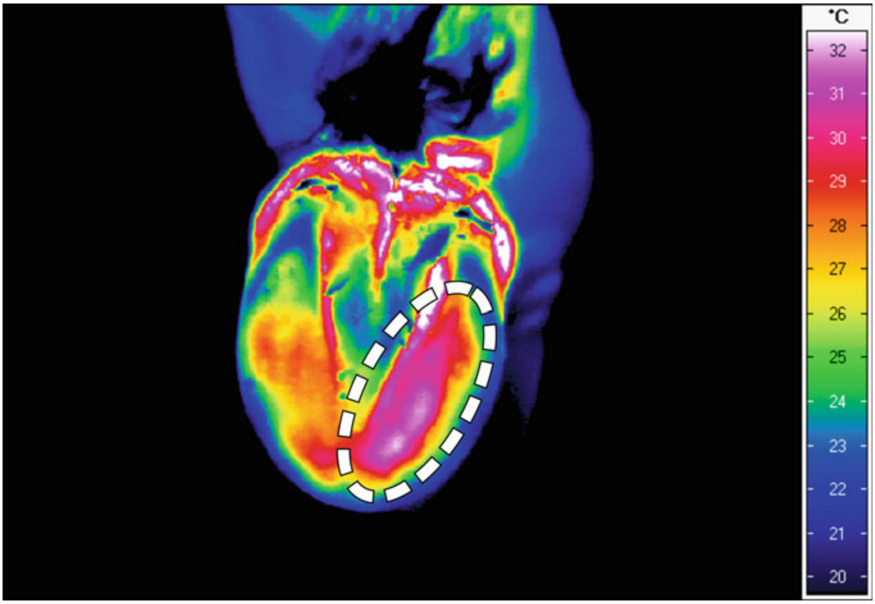

Fig. 11.10 Thermogram of the *left* hoof sole from the solar aspect, illustrating an abscess in the medial aspect of the hoof sole (right side, indicated by dashed circle). Figure obtained from Soroko and Davies Morel [35]

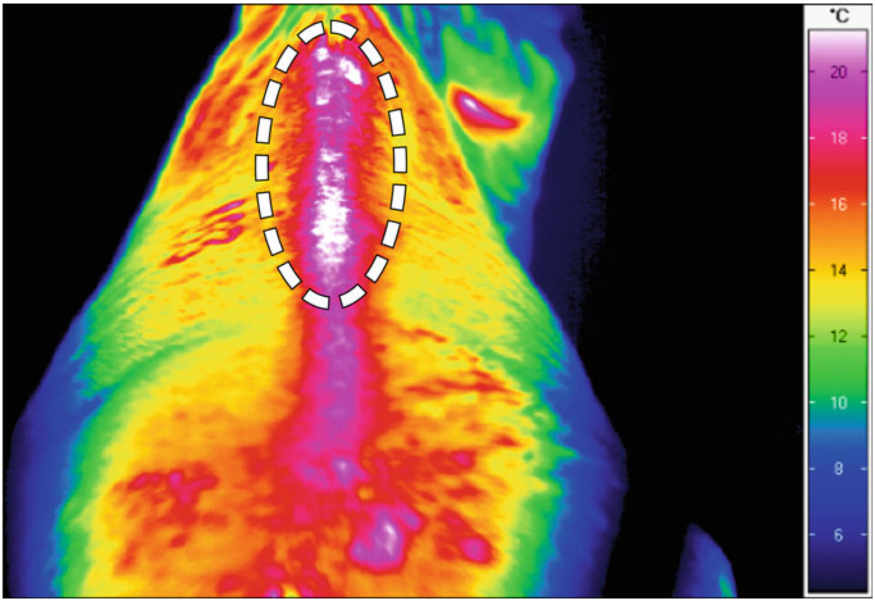

Fig. 11.11 Thermogram of the back from dorsal aspect, illustrating inflammation of the spinous processes of the thoracic vertebrae (indicated by dashed circle)

physically unable to perform because of early tarsal joint arthritis which was confirmed by thermography. However, no changes were detected in radiographic examinations at that stage. The study demonstrated that the early signs of arthritis can be detected by thermography prior to confirmation by radiographic examination. Later, Eddy et al. [37] correlated thermography findings with radiographic, ultrasonographic and scintigraphic methods in a group of 64 horses affected by lameness. Thermography correlated with ultrasonographic examination in 10/15 cases (66.7%), with scintigraphy in 15/20 cases (75%), but with radiography in only 15/29 cases (51.7%), suggesting that thermography may only have a limited ability to detect some of the subtle or chronic bony injuries which cause lameness. During the assessment of tendon injury thermography examination did not correlate well to the structural reorganisation of the tendon matrix as assessed by ultrasonography [51].

In cases of back pain, thermography can localise the exact site of the lesion. In a case of subluxation of the third lumbar vertebra, where the utility of radiography was limited due to the large mass of overlying soft tissue, thermography was able to indicate the area of injury [15]. Kold and Chappell [28] investigated the effectiveness of thermography in detecting clinical inflammation of the back. Thermographic imaging was successful in identifying inflammatory activity of the superficial soft tissue overlying the thoracic vertebrae and the sacroiliac area as a result of injury. It has been suggested that thermography can also help to locate the site of pain, allowing other diagnostic imaging methods to work more effectively

[49]. Fonseca et al. [48] evaluated the effectiveness of thermography and ultrasonography in combination for detecting back abnormalities in Western Quarter Horses. Thermography was used to locate the area of the lesion, and ultrasonography was used to characterise the lesion. This combination was found to be very efficient in thoracolumbar lesion diagnosis. However, not all abnormalities diagnosed ultrasonographically were detected by thermography: in particular, thermal imaging failed to detect kissing spine.

11.2.3 Thermography Sensitivity for Detecting Subclinical Inflammation

Thermography may be used to diagnose subclinical inflammation before the onset of clinical signs of pathology. Strömberg [36] demonstrated the use of thermography to identify pathological changes in the superficial digital flexor tendon prior to the appearance of clinical inflammation. Vaden et al. [17] and Bowman et al. [43] both used thermography to detect subclinical arthritic changes. Other studies also reported the use of thermography to monitor subclinical signs of inflammation in the distal parts of the limbs up to two weeks before the onset of clinical lameness and swelling [16, 45]. Turner et al. [45] reported the successful use of thermography in predicting distal limb tendon, fetlock, carpus, and tarsus injury in Thoroughbred racehorses. The specific purpose of the study focused on predicting injuries before they became clinically evident, and also on determining how well thermography harmonised with trainers' concerns. The authors concluded that thermography was a valuable tool in preventing lameness by allowing early treatment, or changing the training system in response to thermographic findings.

Defining more precisely the indicators of subclinical inflammation would allow quick and practical thermographic diagnosis to better protect horses from injury. Turner [16] has shown that temperature differences of more than 1 °C over 25% of the compared body area can be considered to be abnormal. In another study [44] a temperature change of 1.25 °C was considered indicative of subclinical inflammation in the distal limb. The early stages of bucked shins were detected by Turner [16] when local temperatures were higher (1–2 °C) over the dorsal 3rd metacarpal bone compared to the surrounding areas. In human studies a much smaller body surface temperature difference (0.4 ± 0.3 °C) between left and right side has been reported as indicative of an abnormality [52].

11.2.4 Thermography in the Study of Neurological Disorders

In a horse with Horner's syndrome (a neurologic disease involving nerve paralysis of the sympathetic nervous system around the head and neck), Purohit et al. [53]

demonstrated a local increase of body surface temperature of 2–3 °C due to vasodilation in the denervated area. Research by Waldsmith [54] and Waldsmith and Oltmann [55] indicated that regional nerve anaesthesia caused an increase in body surface temperature secondary to vasodilation from sympathetic blockade, whereas Holmes et al. [56] described local perineural anaesthesia as having no effect on body surface temperature in the forelimbs. Denoix [57] however, reported that nerve injury results in a decrease of body surface temperature.

11.3 Application of Thermography in Monitoring Rehabilitation

11.3.1 The Use of Thermography in Monitoring the Effectiveness of the Healing Process and Medicine Application

Thermography has been used in rehabilitation as a tool for monitoring the effectiveness of the healing process. Ghafir et al. [58] studied the use of intra-articular corticosteroid therapy in horses with arthritis. During the healing process thermography quantified the response to anti-inflammatory medication. Purohit and McCoy [15] used thermography to monitor the effectiveness of anti-inflammatory therapy. Experimental horses had an inflammatory response induced in the area of the metacarpal bones and anti-inflammatory benzydamine was injected 24 h later. Thermographic images of the distal limbs demonstrated a reduction of inflammation by indicating a decrease of temperature. When the warmth of the affected area was no longer detected by palpation and the horse appeared sound, the thermographic image continued to indicate an increased temperature. Thermography was also used to monitor corticosteroid treatment in amphotericin B induced carpal and tarsal arthritis in ponies [43]. A group of experimental clinically-healthy ponies were injected with 10 mg of amphotericin B to induce arthritis either in the carpal or tarsal joint. After arthritis induction, the joint was treated with 100 mg of corticosteroid in order to decrease the time of healing, and its effectiveness was monitored by thermographic imaging. In the case of the carpal joints, there was no significant difference in the rate of return to normal thermal patterns between the treated and untreated group. However, in the case of the tarsal joints the treated group returned to normal thermal patterns significantly faster than the control group.

The treatment of Horner's syndrome with an $\alpha 2$–adrenergic agonist has also been studied using thermography [53] in two horses presenting with clinical signs of the disease. Facial thermographic images were recorded before, and 30 min after application of treatment. A decrease in facial temperature of 2.8 and 3.7 °C in the two horses demonstrated the effectiveness of treatment.

Another study has indicated thermography can be used in detecting temperature differences of the forelimb before and after isoxsuprine administration [59]. This drug is traditionally used to treat navicular disease and sesamoiditis, both of which cause an ischemic effect [60, 61]. Maximal temperature was significantly ($p < 0.05$) higher in the treated than the control group, 2.2 °C (for horses treated with 0.9 mg/kg) and 1.8 °C differences (for horses treated with 1.2 mg/kg) in the distal part of the limbs; indicating thermography to be a sensitive tool for monitoring the effectiveness of isoxsuprine administration. A similar conclusion was drawn in a study of horses with navicular disease which were orally administered with 0.6 g/kg of isoxsuprine hydrochloride paste twice a day for 6–14 weeks. The results revealed a significant temperature increase in the distal limb which occurred from 90 to 480 min after drug administration [62]. Contrary conclusions have been presented by Harkins et al. [63], where thermography examination of the forelimbs detected a significant decrease in the superficial temperature following isoxsuprine injection 30–240 min after injection. Thermography was able to detect a temperature decrease of forelimbs, which was apparent for no more than 4 h. Differences between the above studies could be associated with the route of administration, (injection versus oral).

11.3.2 Monitoring Recovery of Muscle Strain, Inflammation and Myopathy

In physiotherapy practice, thermographic examination can help to locate the body areas potentially susceptible to injury and, in the case of an injury, to monitor the treatment progress. It helps the equine physiotherapist to determine the body areas requiring treatment and ensure quick and efficient recovery to full athletic performance.

Muscle injuries, such as muscle stress, post exercise fatigue and azoturia are common causes of lameness in horses and are recognised as physiological disturbances [64]. Thermography can detect temperature changes associated with muscle strain (Fig. 11.12), muscle inflammation (Fig. 11.13), caudal thigh myopathy and croup myopathy [65, 66]. Thermography may have important clinical applications in the assessment of individual muscle injuries which are difficult to diagnose [16]. Once the area of inflammation is determined, physical therapy can be applied directly to that area. Then treatment and rehabilitation, such as massage or therapeutic ultrasound, can be applied more specifically [66].

The effectiveness of treatment of the thoracolumbar region has also been established by thermography. von Schweinitz [67] used thermography to monitor acupuncture therapy in a case of neuromuscular disease. Han [68] reported that an affected neurological site increased its temperature by more than 5 °C within half to three-and-a-half hours after acupuncture in a group of treated horses. Thermography has also been demonstrated to be an effective method of diagnosing chronic pain [27].

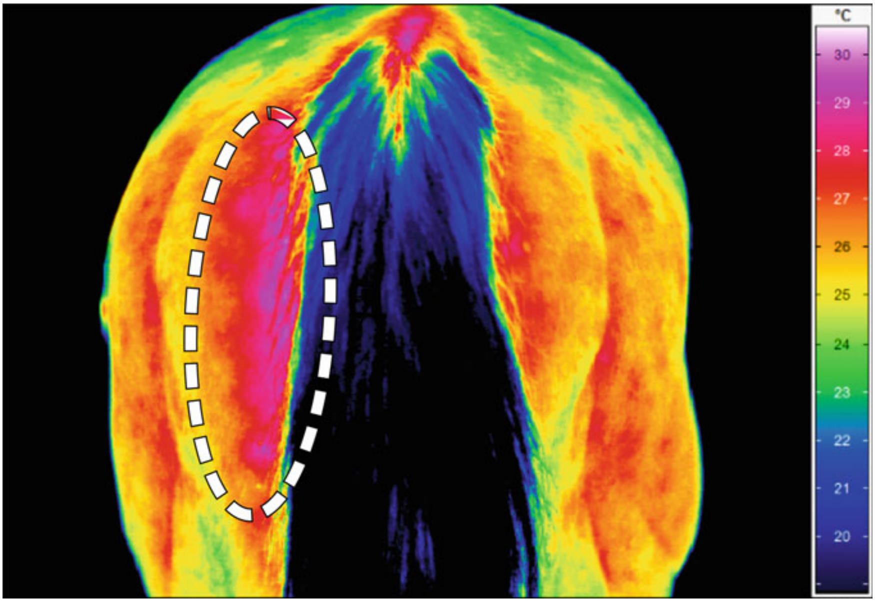

Fig. 11.12 Thermogram of the croup (caudal aspect), illustrating semitendinosus muscle strain of the *left* side of the croup (indicated by dashed circle)

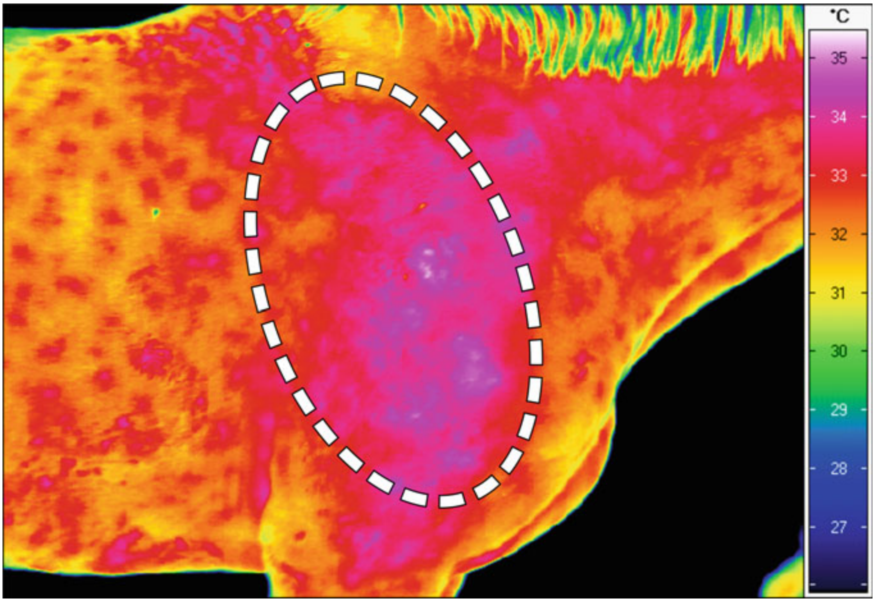

Fig. 11.13 Thermogram of the *right* side of shoulder (lateral aspect), illustrating scapula muscle inflammation (indicated by dashed circle)

Levet et al. [69] studied the use of thermography for monitoring the development and recovery of cast sores on the distal parts of the limb. Thermography was able to detect superficial and deep dermal sores, which was useful in deciding the optimal time for cast change, avoiding serious cast complications.

11.3.3 Monitoring Body Surface Temperature Changes Associated with Rehabilitation Exercise in Horses on a Treadmill

Water treadmill exercises are helpful for horses undergoing rehabilitation processes after injuries of the back and limbs [70]. Water treadmill exercise is an aerobic activity which increases blood circulation in the working muscles [71]. Thermography has the potential to assess the changes in blood flow that reflect the working muscles undergoing rehabilitation in an aquatic environment. In the study presented by Yarnell et al. [72], thermography was used to assess surface temperature changes in the hindlimb as a measure of muscle activity and so inform rehabilitation management. The study found an increase of the body surface temperature of the hindlimb at the onset of exercise, and temperature increased until the end of exercise on the treadmill. There was a significant difference in hindlimb surface temperature when comparing exercise on a dry treadmill and with water at the level of the coffin joint and carpus joint ($p < 0.0001$).

11.4 The Application of Thermography in Horse Performance

11.4.1 The Influence of Exercise on Body Surface Temperature Changes

Body surface temperature is indicative of transformations occurring in the horse due to exercise. Training entails, among other things, changes in the function of the respiratory and circulatory systems. These changes occur simultaneously in both systems and in an integrated way, as part of the body's reaction to maintain homoeostasis. During training the circulating blood volume increases, which has a beneficial effect on the stability of the circulatory system parameters and thermoregulation during exercise [73, 74]. The increased blood circulation results in increased venous return and a raised cardiac output. During exercise muscles, tendons, ligaments and bone are subject to overloads. This affects the intensity of biochemical transformations taking place in individual tissues. Muscles increase their oxygen uptake from blood flowing through blood vessels. This contributes to increased skin circulation and thus to improved dissipation of excess heat to the environment [75]. Simon et al. [76]

Fig. 11.14 Image of a horse working on a treadmill in walk

demonstrated the influence of exercise on body surface temperature. Thermographic examination of horses was performed before and after exercise on a treadmill (Fig. 11.14). The temperature of the upper part of the body after exercise was increased by 6 °C, whereas the distal parts of the limbs were increased by 8 °C. Thermographic examinations demonstrated there was a significant temperature difference between measurements made before exercise and 15 min after exercise, and that significant differences remained evident up until 45 min after exercise It was also found that muscular areas in the upper part of the body returned more quickly to the pre-exercise temperature, compared to the distal parts of the limbs.

11.4.2 Changes of the Equine Musculoskeletal System During Physiological Effort Measured by Thermography

Constant overloads of the equine musculoskeletal system in response to training [77] can cause abnormalities associated with painful conditions or diseases, leading to loss of performance [4]. The physical demands on the horse are dependent on the type of training and the skills of the rider [78, 79]. During training horses put particular strain on the distal parts of the forelimbs and back, leading to frequent injuries in these areas [4, 45, 80]. The distal bones and digital flexor tendons of the forelimbs are subjected to extreme overloads [81], which predisposes the horse to injury [82]. It is therefore important to develop an understanding of the physiological response of the muscular system during exercise in order to determine the most appropriate training program for the horse.

Soroko [83] documented abnormalities of the forelimbs associated with strains and overloads using regular thermographic examinations in racehorses. Other recent studies [26, 84–87] have investigated the use of thermography for monitoring changes of horse surface temperature resulting from exercise, and a model for temperature distribution at the surface of the forelimbs and hindlimbs has been developed. The temperature of the limb surfaces increased significantly with exercise. It was demonstrated that the precise body surface temperature depended on the training intensity and was considerably higher in forelimbs (29.35 °C in mares, 27.09 °C in stallions) in comparison to hindlimbs (28.99 °C in mares, 27.65 °C in stallions) [29]. Increased body surface temperature persisted for more than half an hour post exercise. Measurement of the horse's body surface temperature after exercise was useful to monitor the impact of training on body surface temperature changes and to assess the training [88]. In further studies, a model of the horse's temperature before and after exercise, and after recovery was determined. The rectal temperature, pulse rate and blood parameters, as well as environmental factors were taken into consideration and correlated with body surface temperature patterns. It was concluded that body surface temperature patterns depend on exercise, and that thermography could be useful in the evaluation of the work of individual parts of the body in sport performance [84]. Assessment of body surface temperature can indicate inflamed areas that could also account for a reduction in athletic performance [45, 89].

11.4.3 The Effect of Long Term Training on Body Surface Temperature Changes in Distal Part of the Forelimb and Back

According to Evans et al. [90], constant stress of the musculoskeletal system during intensive training increases its blood supply. In a classic thermographic study by Cena and Clark [91], the leg surface temperature of professional athletes was significantly higher than that of college students even before exercise (31.2 vs. 30.3 °C respectively).

Thermography has been found to be a valuable aid in the assessment of long term training on body surface temperature changes in racehorses [45]. It was found that the temperature of the back and the distal parts of the forelimbs in racehorses at rest was increased by long-term training [89]. In the study by Soroko et al. [86], ten months of regular thermographic examination of racehorses allowed the identification of the most important body regions to be monitored for the effects of training. These areas included the distal parts of the limbs (carpal joints, 3rd metacarpal bones, left fetlock joint, short pastern bone, tarsus joint), the majority of which were on the left side. Possibly, as the horses during racing and exercise were loaded on the right front limb due to the clockwise race track, when resting they were overloading the opposite side [86]. However, this contrasts with the study by Strömberg [36] in which horses trained in a counter—clockwise direction had increased left forelimb temperatures of 0.4–2.2 °C compared to the opposite side after exercise.

In further research Soroko et al. [12] found that the thoracic vertebrae, the left third metacarpal bone, and the left fetlock joint were significantly warmer in horses undergoing intensive training than in horses undergoing light training The data from this study suggest that ambient temperature, breed and training intensity level are the most important factors affecting skin temperature at the distal parts of the forelimbs and the back. Thoroughbreds were significantly warmer than Arabian and Polish Halfbreed horses at these body sites. Similar results were found in a previous study of racehorses where the distal parts of the hindlimbs of Thoroughbreds were also warmer than Arabians and Polish Halfbreed [92]. These temperature differences could be associated with varying thermal insulation of the coat in different breeds [93, 94]. Further studies demonstrated that the forelimb and hindlimb of racing mares were warmer compared to stallions [29, 92]. This may be explained by the reported higher metabolic activity in mares compared to stallions at the same level of training intensity [95].

Identifying the key thermographic diagnostic areas will help in detecting pathological conditions during training. This is particularly important in racehorses, where immediate diagnosis might help to maintain their health and condition, positively influencing their further athletic career. It is therefore suggested that prophylactic thermographic examination of key areas of the distal parts of the limbs and back should be carried out as a routine examination every 2–3 weeks for horses in regular training.

11.5 Application of Thermography in Monitoring the Use of Illegal Performance-Enhancing Procedures

11.5.1 Use of Thermography in Detecting Abnormal Temperatures Caused by Chemical and Mechanical Abrasion of Performance Horses

Thermography has found application in detecting abnormal temperature caused by chemical and mechanical abrasion of performance horses, particularly used to induce hypersensitivity in the distal parts of the limbs, for example of gaited show horses [96]. Kaemmerer and Buntenkötter [97], as well as Stephan and Görlach [98], suggested that a thermographic image can also be used to detect the application of drugs and their effects. Turner and Scroggins [99] thermographically detected the application of an irritant to the perineal region to enhance tail lifting in a show horse. In another paper, thermography was successfully used for detecting inflammatory chemical irritants applied topically (e.g. 10% mercuric iodide) or injected subdermally (e.g. isopropyl alcohol), and induction of hypersensitisation using limb bandages containing metallic objects. Irritants were applied to the pastern area, and metallic irritants contained in limb bandages were applied to the metacarpal area to induce hypersensitivity [100]. Thermography indicated changed thermal patterns after a single application of an irritant (mercuric iodide) which persisted for 6 days. Metallic bottle caps within the leg wraps could be thermographically detected up to 24 h after application. A limitation of this application of thermography, however, is a lack of specificity: an increase in temperature may not be due to a specific drug, and equally undetected subclinical injuries could create inflammatory patterns similar to those caused by illegal agents.

Van Hoogmoed and Synder [38] also used thermography to monitor palmar digital neurectomy, which involves cutting both palmar digital nerves to mask lameness. There was a significant temperature increase in the neurectomised limb on the first day of treatment, which persisted up to day 6 post-treatment. It is suspected that nervous interruption causes a vasodilator effect, persistent for a short period of time until the vascular system compensates, influencing a return to normal circulation. In an earlier study by Purohit and Pascoe [101], thermographic examination of neurectomised limbs indicated no temperature differences between neurectomised and non-neurectomised horses three to six weeks after the operation.

11.5.2 Use of Thermography Under International Equestrian Federation (FEI) Rules as a Complementary Diagnostic Method for the Detection of Artificially Induced Temperature Changes in Sport Horses' Limbs

The FEI approves thermography as a complementary diagnostic tool for detection of artificially-induced temperature changes in the limbs of jumping horses. Standard thermographic examination methods to diagnose hypersensitivity of the limbs appear in Annex XI of the FEI Veterinary Regulations (the "Annex XI Protocol" 2012). These regulations contain a detailed thermographic examination protocol together with the required supporting clinical examinations. Horses with hypersensitive limbs may be disqualified on the basis of horse welfare and fair play. However, limb hypersensitivity can also be produced by a range of normal occurrences such as insect stings or accidental self-inflicted injuries. Hyposensitivity could also result from traumatic or surgical cutting of the nerves in that area of the limb (i.e. neurectomy). For this reason thermographic examination, combined with clinical examination, is used as the first step prior to taking a horse for further investigation [102].

11.6 Application of Thermography to Assess Saddle Fit

11.6.1 Importance of the Correct Saddle Fit

Changes of the body surface temperature across the back area can be associated with pathological conditions caused by an incorrectly fitted saddle [78, 103, 104]. A saddle that does not fit the horse correctly has potentially far-reaching consequences for horse health. An ill-fitting saddle is associated with back pain, uneven sweat marks, white hairs, abnormal hair wear and soft tissue injuries or spinal stress fractures. The clinical manifestations vary from overt lameness and pain on palpation, to gait alterations or behavioural changes [105–107]. The fit of the saddle for both the horse and rider must be evaluated. A correctly fitted saddle should distribute weight evenly via the panels on the horse's thoracic region, with clearance of the spinous processes by the gullet.

11.6.2 Application of Thermography in Saddle Fit Examination

The dynamic interaction between the saddle and the back of the horse can be evaluated by thermography to identify any problems with incorrect saddle fit. Thermal patterns caused by the tack while the horse is being ridden are indicative of the heat generated in areas of greater interaction with the saddle, and the physiological effects of riding on the back of the horse [108]. For thermographic saddle-fit assessment, the horse should be tacked up with saddle pad and tightened girth. Riding should take place for at least 20 min in walk, trot and canter. Thermographic examination of the back should be performed immediately after untacking the saddle. According to Turner "The pictures reveal the temperature fluctuations of the underside of the saddle and the back of the horse" (Fig. 11.15). The image of the back is interpreted according to the symmetry of the temperature distribution. In a correct saddle fit, the back surface temperature distribution should be the same on both sides of the spine. Locally warmer areas indicate greater interaction between saddle and back, cooler areas indicate less interaction. In addition, thermographic imaging of the saddle pads can assist with saddle fit.

A common example of incorrect saddle fit is a greater interaction on the back at two points: at the level of the pommel and the cantle on both sides of the back (Fig. 11.16). This indicates a "bridging saddle". Conversely a "rocking" saddle indicates contact along the panels but not toward the pommel or cantle. Arruda et al. [103] carried out thermographic examination of 62 saddles used on 129 jumping horses. The images obtained allowed evaluation of a range of features, including contact between the saddle and the spine; asymmetry in the area of interaction between the saddle panels and the back of the horse and asymmetry between the saddle panels. The main results indicated an uneven (asymmetric) pressure across

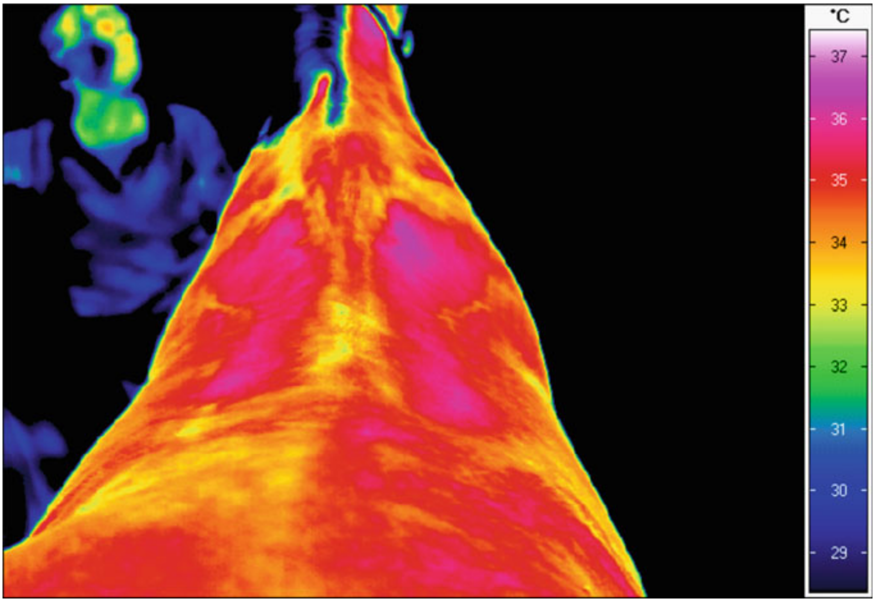

Fig. 11.15 Thermogram of the dorsal aspect of the back, taken 20 min after training in a jumping saddle. This is an example of a correct saddle fit. The back surface temperature distribution is equal on both sides of the spine

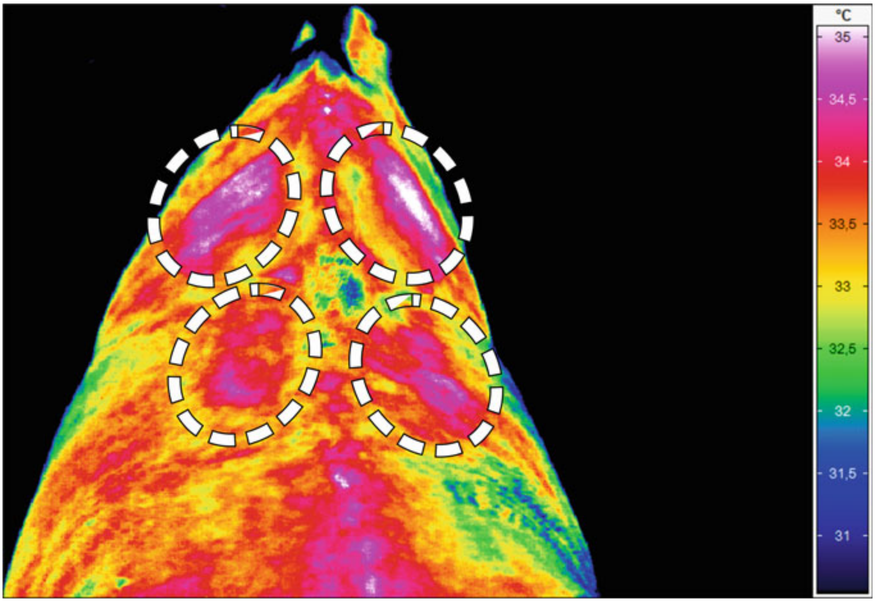

Fig. 11.16 Thermogram of the dorsal aspect of the back, taken 30 min after training in a jumping saddle. The pommel and cantle of the saddle has greater interaction on the back indicated by dashed circles. The middle part of the saddle seat has no contact with the back. This is an example of a bridging saddle. Figure obtained from Soroko and Davies Morel [35]

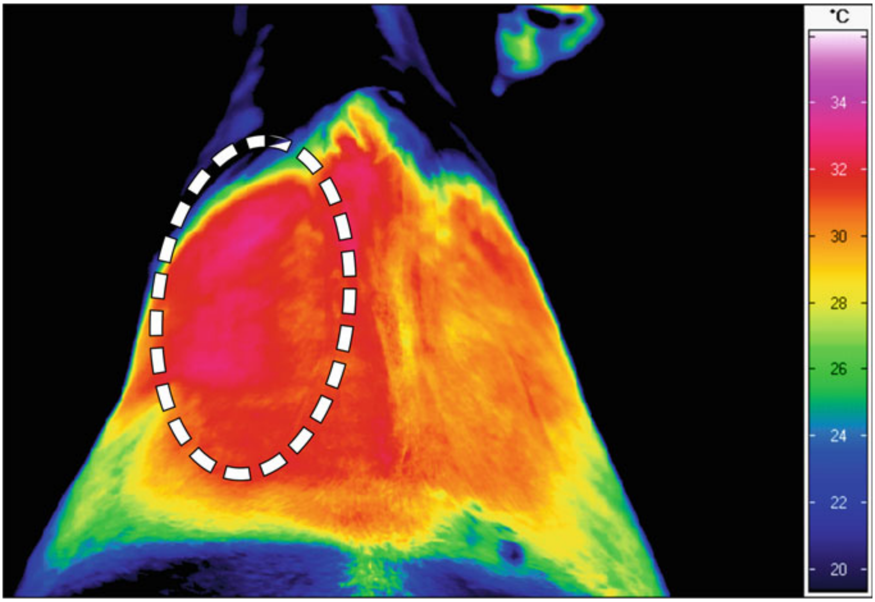

Fig. 11.17 Thermogram of the dorsal aspect of the back, taken 20 min after training in a jumping saddle. There is greater interaction on the left side between the saddle and the back (indicated by a dashed circle)

the back and spine in 55.8% of horses. Saddles had direct contact with the spine in 37.2% of cases and asymmetry between the saddle panels was evident in 62.8% of cases (Fig. 11.17).

In thermography saddle fit assessment it must be remembered that there are many external factors that also influence the final thermographic image. According to the Society of Master Saddlers (2013), thermography assesses heat, which does not always have a relationship with force and can be an unreliable tool for accurate saddle fit. Therefore, the interpretation of the thermogram requires careful consideration and can be used only as an additional tool in the assessment of saddle fit.

11.7 The Application of Thermography in Measuring Stress and Assessing Horse Welfare During Training

11.7.1 Use of Thermography in Assessing Eye Temperature as a Means of Detecting Acute and Chronic Stress During Horse Performance

Horse welfare and stress-related disorders are becoming subjects of growing interest for increasing numbers of horse owners, breeders and riders. Several studies have shown that thermography represents a useful method to assess acute and chronic stress in sport horses [109, 110]. In a stressful situation the hypothalamic-pituitary-adrenal axis is activated, along with peripheral vasodilatation due to the parasympathetic activation that follows the initial sympathetic response, causing changes in the animal's heat production and heat loss. A number of studies have shown that the temperature of the eye is a good indicator of changes in body temperature due to physiological and psychological stress. Cook et al. [111] investigated eye temperature and saliva cortisol concentration to measure adrenocortical and metabolic activity in horses before and after an injection of adrenocorticotrophic hormone. They reported a correlation between eye temperature and cortisol concentration. Similar results were presented by Warren et al. [112], who found significant correlations between maximum eye temperature and both salivary and plasma cortisol concentration after adrenocorticotropic hormone injection. Further studies have investigated stress in sport horses by measuring changes in eye temperature [113]. Increases in eye temperature were found to correlate with increases in salivary cortisol during clipping in a study by Yarnell et al. [110]. Bartolomé et al. [114] demonstrated a correlation between increased maximum eye temperature and heart rate after jumping competitions.

11.7.2 Use of Thermography in Assessing Changes in the Body Surface Temperature as an Indicator of Stress in Response to Different Training Methods

Within international equestrian sport, there is much debate surrounding the stress associated with different training methods, in particular in relation to the head and neck position [115]. Hall et al. [116] found increased maximum eye temperature in horses lunged with a Pessoa training aid (held responsible for increasing stress during training). Becker-Birck et al. [117] studied whether hyperflexion (defined as the over flexion of the neck dorsoventrally to the point where the chin touches the pectoral region) presented an acute stress to horses. The study measured superficial body temperature at the neck, along with salivary cortisol concentration and heart rate in horses lunged with restricted (hyperflexion) and non- restricted neck positions. No acute stress responses to hyperflexion were observed.

McGreevy et al. [115] measured stress by means of eye and facial skin temperature in horses wearing nosebands with a flash strap that restricts jaw movements during training. Tightened nosebands caused an increase in eye temperature compared with the baseline values ($p = 0.016$), and the tighter the noseband was fastened, the cooler became the surface temperature of the head. Recently, there has also been interest in the measurement of equine eye temperature for the detection of fever [118].

11.8 Conclusions

The power of thermography lies in its ability to provide physiological information about a “physical change” [31, 119]. Thermography specifically increases the accuracy of diagnosis by confirming inflammation and indicates in which area to concentrate further diagnosis. It can play an important complementary role in the early detection of pathology, and help to prevent the financial losses associated with delayed diagnosis [9, 16, 17, 44]. The development of improved infrared technology, and better availability of this type of equipment, should contribute to more extensive use of thermography in veterinary medicine. This will be applicable not only to horses, but also to other animals.

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Chapter 12
Issues and Future Developments of Infrared Thermography in Sports Science

Jose Ignacio Priego Quesada and Ricardo Vardasca

Abstract Although currently infrared thermography has a great number of applications in sports science, there are a number of different aspects that need to be investigated in order to improve the technique, the methodology, the analysis and to increase its application areas. In this chapter, we discuss the issues with and possible developments in infrared thermography in sport science, in order to facilitate future R&D.

12.1 Introduction

As noted in previous chapters, infrared thermography has a great number of applications in sport science. Its use can be of great value in different areas such as sports medicine [1], clothing design [2] or physiology performance assessment [3]. The use of infrared thermography in sports science has been growing continuously since the last decade. Therefore, infrared thermography has a great present in sport science.

However, it is important not to forget that the use of thermography in sports science began not long ago. For this reason, different aspects and developments need to be studied with greater detail in order to improve this technique in the future. Infrared thermography presents a great potential for improvement in

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sports science. This context implies a positive vision of the future of thermography in which the number of applications can increase, and the methodology and analysis can improve.

This chapter aims to discuss all these thermography issues that need to be investigated and improved in sports science. Through this discussion, it is expected that the present chapter will facilitate future research in academia, and the development for manufacturers of infrared thermography cameras. Moreover, this discussion may be able to discern and imagine how infrared thermography will be used in sports science in the future.

The chapter will discuss the technical aspects of thermal imagers (features, quality assurance principles and software challenges). Additionally, the chapter will discuss aspects related to some of the main methodological problems of thermography in sports science during experimentation (e.g., sweat issue or when and how to measure) and data analysis (thermal variables, skin temperature data reference, etc.).

12.2 Infrared Camera Features

Infrared thermography cameras have improved in recent decades, resulting in a powerful and reliable technique [1]. Although cooled cameras present a better image quality and thermal sensitivity, uncooled cameras are the most used type of cameras in sport science due to their associated benefits: more accessible in price and maintenance, smaller and easier to use [4–6]. The quality of uncooled infrared cameras is approaching the cooled instruments, which have a limited time of operation.

The most important features that researchers demand in their infrared thermography cameras are the sensors' array size, the noise equivalent temperature difference (NETD), and the repeatability of the measurement [7]. However, the minimum requirements for infrared camera features for sports and medical research are an sensor array size of 320 × 240 pixels, an NETD of <50 mK at 30 °C and a measurement repeatability of ±2 °C (over the whole camera temperature range) or ±2% of the overall temperature reading [8]. Some cameras present a better measurement repeatability (±1 °C or ±1%); however, these cameras have a more inaccessible price. Experiments performed by our research groups have shown us that this error in accuracy is systematic. This means that the error between the thermographic value and the real value is always the same. Because of this, when comparisons are made of images with the same camera, the error of the difference between them does not depend on the measurement repeatability, but rather on the NETD. Although in these cases the error of the difference between measures is lower, the measurement repeatability is maintained in order to determine the absolute temperature of the region of interest (ROI). Furthermore, the capacity to determine accurately the absolute temperature is of great importance for some applications. Some examples are fever screening [9] (Fig. 12.1) or the

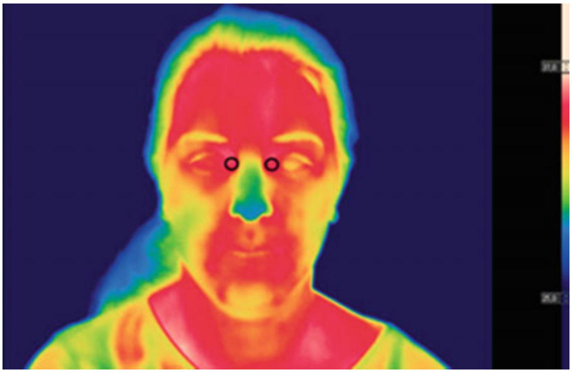


Fig. 12.1 Example of infrared thermography for determining a febrile state

determination of high skin temperatures during high intensity exercise in hot environments in order to predict impairment of aerobic performance [10, 11]. For these reasons, the improvement of the accuracy of the infrared cameras is one of the features that researchers expect manufacturers to improve.

On the other hand, the curvature effect of the skin surface leads to an error in the measurement of the skin temperature, because it causes more thermal energy reflection [12]. Different authors have suggested the development of **3D infrared thermography** by the combination of 2D thermography with other image systems (e.g., photographic systems or MRI/CT) in order to improve the accuracy and the reliability of the technique [13–15]. Since the actual existing systems of thermal imaging are 2D, the only method to create 3D images is to estimate the temperature values of pixels from another. There are three basic principles to do this: using the nearest neighbor (closest pixel), bilinear (average of 9 neighbors) and bicubic (average of a neighborhood of 16 pixels) interpolation methods [16]. Thermal imaging pixel values are radiometric and directly obtained from the energy perception of the camera sensors. If artificial new pixel values are estimated from others then new errors are generated. From a comparison study [16], when using pixel reconstruction in thermal imaging, the best method is the most basic—the nearest neighbor—although it is not recommended for human assessments since the temperature range is very narrow and it will have an high impact on the measurement results. Despite the nice exemplificative images from the 3D thermography current developments, they are not being used at the moment in sport science.

12.3 Quality Assurance Principles

Every measurement method is an objective assessment; in terms of warranty, its quality, and basic quality assurance is needed. There are two types of quality assessment, within capture and periodically.

For both types of quality assurance, a calibration source is recommended, normally a black body (a device that has the ability to absorb all incident radiation at all wavelengths and only emit thermal radiation at a single temperature and known wavelength). For examination quality assurance [4] it is recommended that one image be captured from the calibration source at the beginning of the examination and the other at the end. If the value of the ROIs of the images taken from the reference differ by more than the camera repeatability, it is recommended that the whole examination be repeated and that a verification be performed in the camera. The other option is to include the calibration source in the field of view of the thermogram taken and to verify the temperature reading within the ROI for examination quality warranty.

Two years after the acquisition of the thermal camera, it is recommended that it be sent back to the manufacturer or any certified center for recalibration, which is expensive. However, there are a few tests that can be easily performed, that allow for better knowledge of the camera and for identification of when it needs to be sent for recalibration. With these tests, you can easily verify, at low cost, the camera start-up drift, long-term drift, offset over temperature range, thermal flooding effect and image non-uniformity [17].

The start-up drift is the time required by the camera to be stable after turning it on. The camera sensors are organized in an electronic array, when it is switched on, it needs some time before starting to capture the images due to undesirable effects such as the warming up of the internal electronics. For the image to be taken in good quality a certain time should be refrained that warrant that equilibrium. To know this, the camera should be placed in front of a calibration source (black body) for a determinate period of time (e.g., 1 h) and images should be taken at a one minute interval, comparing the mean temperatures of the reference ROI, the period of stabilization and possible variation can be determined. The long-term drift can be caused by ageing of the camera electronic components. In order to observe this, the start-up drift test should be repeated periodically and records should be kept of the results; this will help to identify when the camera needs to be recalibrated by the manufacturer or certified body.

Some cameras can present an error in measurements that can be introduced by the camera sensor array readout having different temperature amplifications for different temperatures (offset variation over temperature range). This should be verified every three months. This test can be achieved by introducing a bucket of water to the scene, and specifying different fixed temperature ranges, which should be reduced over time in reductions of 0.5 °C, by adding cold water or stirring the water to make it cool faster. By comparing the reference ROI mean temperature, it is possible to identify differences.

Thermal flooding is an undesired effect in a object surface temperature reading caused by an object of the different temperature (cooler or warm) in another in the scene, affecting its real temperature measurement. The warm causes flooding by stray radiance; this should be verified every month. Two buckets can be introduced in the scene at different temperatures and they can be approximated using one as reference and, verifying the reference ROI's mean temperature, the effect can be calculated. The image non-uniformity happens when the sensor cannot detect the correct radiation of the objects in the corner of the images, resulting in deficiencies of the optical path. It should be also verified periodically (typically every two months) through pointing the camera at a uniform wall, taking a few thermal images, drawing on them two cross-sections at the main diagonal lines and comparing their in temperature distributions; the differences provide the non-uniformities.

12.4 Software Challenges

Thermography manufacturers provide general software for a wide range of uses. In this sense, a software package developed for human and medical assessment is lacking [4, 5], and, more specifically, for a sports science application. Additionally, manufacturers hinder the development of new software by researchers through the encryption of the thermal data in the image file. For these reasons, many thermal image processing techniques that could improve the data analysis have not yet been developed and disseminated to researchers.

The image radiometric file formats are also not uniform throughout the camera manufacturers and even within the same manufacturer, which makes thermal image integration and comparison between different systems and remote centers that have different camera models difficult [18].

Image processing techniques are essential in the application of the infrared thermography assessment [19, 20]. This section is focused on the following issues that are believed to be in the process of being solved through the development of future software:

- The determination of the regions of interest (ROIs).
- The effect of the hair on skin temperature measurement.
- The determination of the number of hot spots in a ROI.

The reproducibility of the determination of the ROIs in image analysis is an important factor for guarantying the accuracy of the results. The subjective and non-standardization of the determination of the ROIs could lead to a lower reproducibility and accuracy of the results [21]. One of the most desired solutions is the use of software packages with an **automatic ROI selection feature** [2, 22–24]. These software package commonly process the thermal images by masks, which provide an outline of the ROI [20] (Fig. 12.2). However, these software packages are not accessible to all users because there is lack of free software packages developed by the manufacturers with this purpose [5].

Image fusion of the software packages can help in the determination of the ROIs, improving the precision and repeatability by the use of anatomical landmarks [1, 25] (Fig. 12.3). This feature also can help to better localize the affected area and the extension of the injury [1].

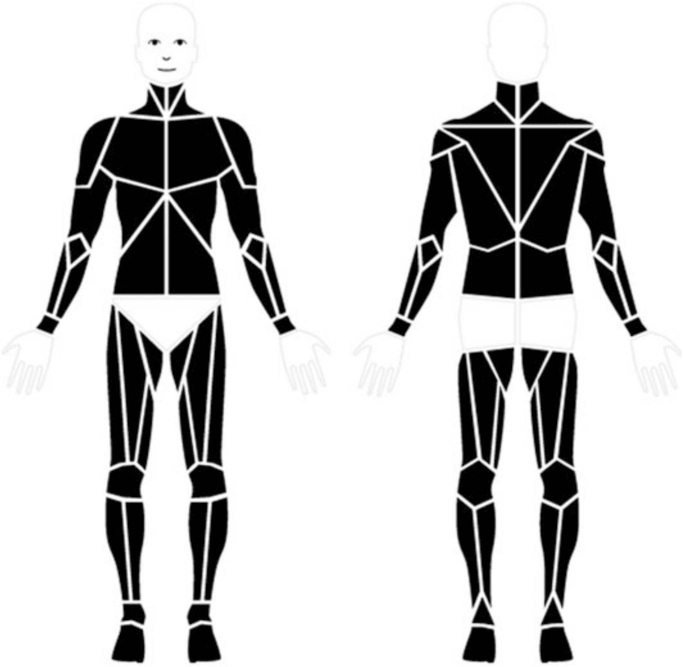
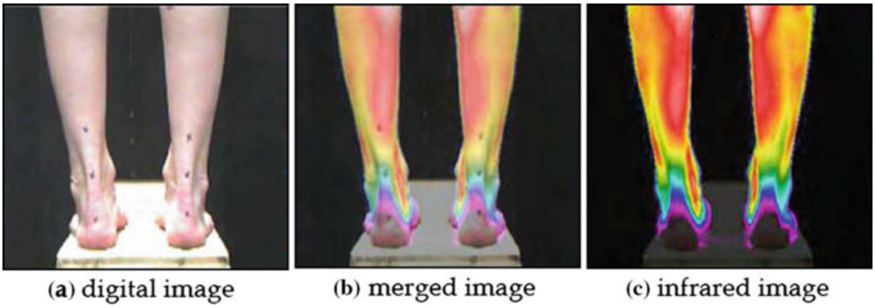


Fig. 12.2 ROI template of the ThermoHuman Cloud Software. Figure provided by ThermoHuman Company



(a) digital image (b) merged image (c) infrared image

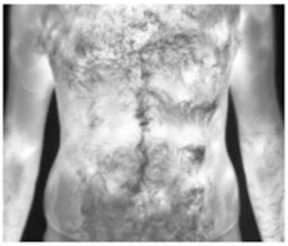
Fig. 12.3 Image fusion. Figure obtained from Hildebrand et al. [25]

Additionally, there are differences between people in the anatomical shapes and sizes, resulting, in most of the cases, in the ROI defined in one person having a different number of thermal pixels compared with a different person [5]. Future software packages would offer the possibility of use different analysis techniques in order to calculate the temperature of an ROI from the same number of pixels in all the participants.

On the other hand, future software packages could help to solve the issue of the **human hair** in skin temperature measurement. Human hair is an avascular structure with a lower emissivity, lower thermal conductivity and then lower temperature [6, 26, 27]. For this reason, the presence of hair on the skin surface could be considered an artifact in the thermal image, resulting in an underestimation of the skin temperature [28]. Although it is common to ask for the participants to remove their body hair some days before the thermography assessment [29–32], this could be inconvenient during participant recruitment. It is probably always the best option to remove the hair, but when it is not possible, future software packages could remove the hair from the image by processing techniques, resulting in an estimated value (known error) of the skin temperature (Fig. 12.4b, c). However, for people with a high body hair density, it is possible that this processing technique would be not valid (Fig. 12.4a). Furthermore, after future development of this processing technique, it would be interesting to assess the utility of this suggested method by assessing the differences with and without this processing technique (by shaving body hair before the measurement).

Finally, a tool for the identification of the **hot spots** could be very valuable. Hot spots could be defined as any area that is at least 0.5 or 1 °C warmer than its surrounding and contralateral side, respectively. Another improvement could be the comparison of the ROIs' histograms [33]. Hot spots were suggested by some authors in medicine as being an interesting variable in injury assessment [25, 33–36]. Furthermore, these hot spots could be related to the perforating vessels (capillarity vasodilation) [33], and then could be an interesting variable to measure

(a) Image without the possibility to process



(b) Original image

(c) Processed image

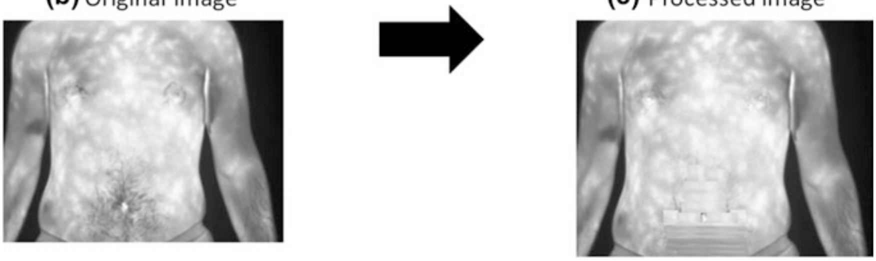


Fig. 12.4 Idea for future image processing technique with the objective of removing the hair from the image

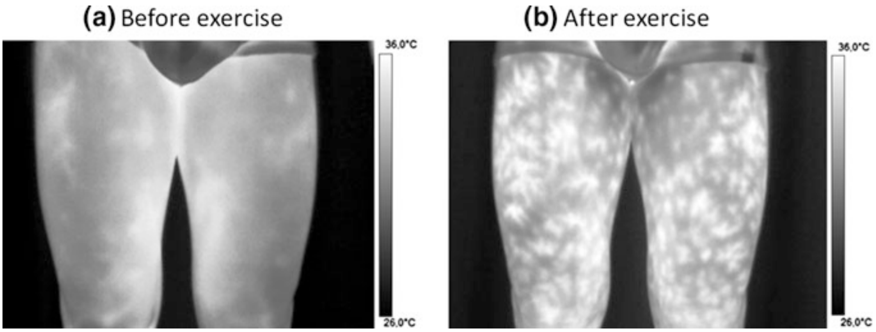


Fig. 12.5 Increase in the number of hot spots after 45 min of cycling

during exercise (Fig. 12.5). However, there is a need for improvement in the reliability and reproducibility of hot spot identification using software [5, 33]. When proper software is developed, it should be performed in studies that analyzed the hot spots during exercise.

12.5 Intraday Skin Temperature Reproducibility

Different intrinsic and extrinsic factors are necessary to control in the measurement of skin temperature [28] in order to reduce variability between participants and between days [21]. In relation to the reproducibility of skin temperature measurement using infrared thermography, McCoy et al. [37] observed excellent reproducibility between days for infrared images from the paraspinal region. Furthermore, Zaproudina et al. [21] found moderate reproducibility in the trunk and poor reproducibility in the limbs. Zaproudina and colleagues suggested that this result was probably due to physiological variability of blood flow in the distal parts of the body [21]. Although reproducibility of skin temperature measurements using infrared thermography was assessed by these studies in baseline conditions, research into the reproducibility of thermal data after exercise is still necessary.

The only study that assessed the reproducibility of skin temperature after exercise using infrared thermography was performed by Priego Quesada et al. [38]. However, the aim of this study was to determine the effect of an intervention (changing saddle height in each season) on intraday reproducibility after cycling exercise. Therefore, this study cannot be considered to be a perfect example of reproducibility research because all the tests were not performed at the same conditions; however, the results are useful to illustrate why future research is necessary. Priego Quesada et al. [38] observed good and very good reproducibility of skin temperature before exercise, and good reproducibility after exercise. However, when the authors assessed the intraday reproducibility of skin temperature variation analysis (difference between post and pre exercise), they observed similar good reproducibility in the trunk, but worse reproducibility in the lower limbs. The authors suggested that skin temperature variations can be more sensitive to an intervention (in this case, changes in the saddle height) than absolute temperatures. For this reason, further studies are necessary in order to investigate the reproducibility of temperature data (absolute temperature values and Δvalues) after exercise.

On the other hand, in the most distal regions of the human body, such as the feet, peripheral circulation is less homogenous, resulting in an increase in the variability of skin surface temperature and reducing the reproducibility of thermographic measurements in that region [21]. As was discussed in the Chap. 10, the foot is one interesting region for thermography analysis with multiple possible applications in sport science. It is possible that, although the reproducibility of the foot is low [21], the effect of exercise may be more constant. Future studies are necessary to analyze the effect of exercise on intraday reproducibility of foot temperature and to compare the reproducibility of skin temperature variation with absolute temperatures.

12.6 Skin Thermoregulation Issues

The human body is homoeothermic; the core temperature is maintained at a constant by the hypothalamus, and there are other body structures such as nerves, blood flow and skin thermal sensors that play an important role in bocy temperature. The temperature within the body can be regulated by autonomic and behavioural means, as shown Fig. 12.6, where the red flux represents the heat transfer path and the green represents the signal path [39].

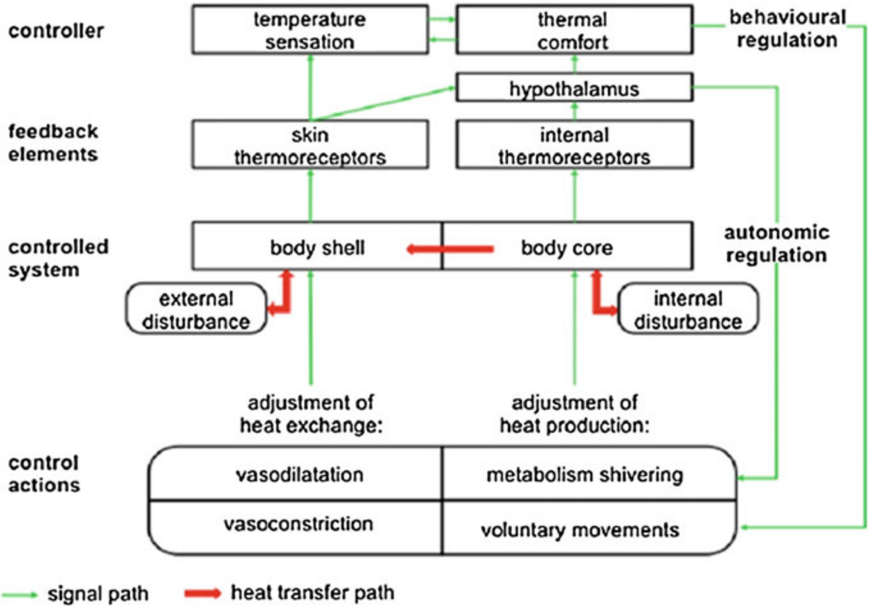


Fig. 12.6 Human body thermoregulation diagram according to Houdas and Ring [39]

Thermoreceptors are spread throughout the human body, internally sensing the temperature close to the organs and peripherally sensing the shell temperature under the skin dermis. Any variation of temperature values is communicated via the nervous system to the body central temperature controller, that is a group of neurons in the anterior part of the hypothalamus, known as the preoptic area. It is this area that receives nervous impulses from the thermoreceptors, mucous membranes and other areas of the hypothalamus. Neurons from the preoptic area generate impulses at high frequency when blood temperature increases and at lower frequency when blood temperature decreases. These impulses propagate to two other parts of the hypothalamus known as the heat-losing center and the heat-promoting center, that when stimulated by the preoptic area set into activity a series of responses that lower or rise body temperature correspondingly. When the sensory system acknowledges a decrease in core temperature, nervous impulses are sent to the preoptic area, which in turn activates the heat-promoting center through hormone production, activating the heat gain mechanisms such as: vasoconstriction (decrease in warm blood flow), shivering (muscle contractions and stretching), and a slow increase of metabolic rate. If a core temperature increase is perceived, the thermoreceptors will send nerve signals to the preoptic area, which generates hormones that inhibit the heat-promoting center and activates the heat-losing center, which in turn activates the body temperature decrease mechanisms such as vasodilatation and sweat gland stimulation, which activate perspiration through the sympathetic nervous system [40].

Many of the thermographic studies in sport science are performed during or after exercise [3, 29, 30, 41–43]. Exercise will result in an increase in core temperature due to the higher metabolic activity [44, 45]. One of the main mechanisms for heat dissipation during exercise is sweating and sweat evaporation [46–48]. It is known that evaporation of sweat results in a decrease in skin temperature. This decrease in skin temperature helps in the dissipation of the core body heat, because it increases the thermal gradient between the core and the skin [11].

Although it is known that sweat evaporation is essential during exercise, the effect of sweat on thermographic measures remains unclear [49] (Fig. 12.7). It was

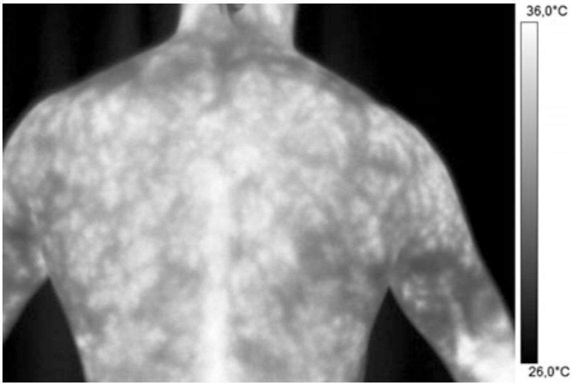


Fig. 12.7 An upper back of a cyclist immediately after cycling 45 min. Sweat was not removed and, visually, layers of sweat were not appreciated

suggested that a film of water on the skin may act as a filter for infrared radiation and that this could lead to an error in the estimation of skin temperature [50]. Therefore, it was assumed that sweat produced on the skin during and after exercise could lead to errors in skin temperature calculation. For this reason, some studies have tried to remove the sweat or water from the skin without friction [51, 52] (Fig. 12.8). However, other studies have indicated that they did not remove the sweat in order to keep the natural process of sweat evaporation and because the relevance of sweat (i.e., without the film of water on the skin) on thermographic

Fig. 12.8 Removal of water layers with absorbent towels without friction

Table 12.1 Advantages and disadvantages of the strategies concerning sweat in thermographic exercise studies

	Advantages	Disadvantages
Remove sweat	• Remove the possible effect of sweat on thermography data	• Possible friction during the removal that increase skin temperature • Reduction of the capacity of sweat evaporation, thus lower capacity of skin temperature reduction
Not remove sweat	• More close to reality because the natural process of sweat evaporation is not altered	• Possible effect of sweat on temperature calculation that could lead to errors

data is still unknown [38, 53, 54]. Table 12.1 summarizes the positive and negative aspects of both strategies.

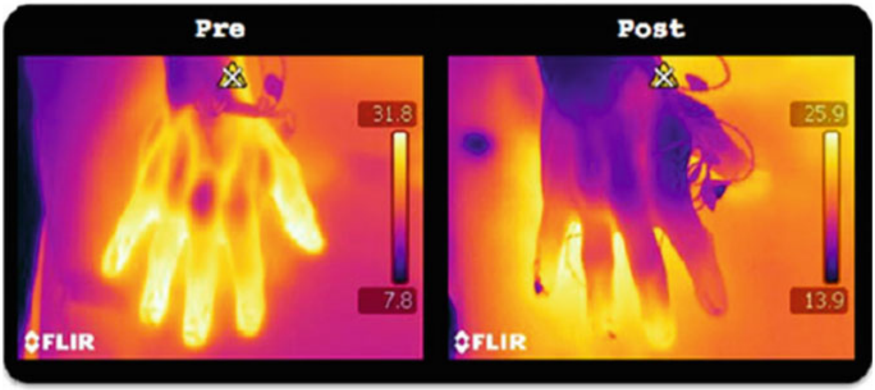
Different reasons make this issue difficult to research. Not having a perfect gold standard for the skin temperature measurement makes it more difficult to know the effect of sweat. In this sense, some comparison were performed between thermography and thermal contact sensors such as thermocouples [49, 55, 56]. However, thermal contact sensors have some other issues in skin temperature calculation. These sensors alter the skin temperature through contact with the sensor and its fixation method on convective and evaporative heat loss [49, 57, 58]. Furthermore, it is hard to know which process (error in temperature calculation by sweat, rubbing, sweat evaporation, etc.) has a greater influence on skin temperature. In this sense, one study tried to compare the differences between thermal contact sensors and infrared thermography during exercise, and during mechanical tests (hot plate system) in order to investigate the agreement between both methods during well controlled dry and wet heat exchange (avoiding thermoregulatory responses) [53]. The results were comparable and the authors assumed that differences between thermal contact sensors and thermography were mainly through the effect of the fixation on skin temperature. They concluded that the accumulation of sweat during cycling is not enough to form a film of water and that the sweat produced under these conditions does not affect the thermographic data [53]. However, further studies are necessary to explore this issue and provide answers to the questions below:

- Does sweat affect skin temperature? In all scenarios, none, or only where the sweat rate is very high?
- If there is an error in skin temperature calculation due to sweat, how great is this error?
- Does removal of the sweat affect skin temperature? How great is this effect?
- Is it necessary to wait for a minimum time after removing the sweat?

Different skin thermoregulation issues could be considered if the study is performed during exposure to a cold environment or to a warm environment.

Two main thermoregulatory effects resulted from cold exposure. First, the vasoconstriction of skin blood flow with the aim of reducing heat loss [59]. Secondly, if there is a severe cold exposure, thermogenesis via shivering, consisting of involuntary contractions of the muscles, is produced, with the aim of increasing heat production [59]. Research into the effect of cold exposure on skin temperature in sport science is especially focused on the human response to high altitude (during exercise or during specific acclimatization/training exercise protocols) (Fig. 12.9) [60–62], and in response to sport medicine treatments such as cryotherapy [63, 64]. Furthermore, in medicine, more of the studies are focused on analyzing the reasons for cold injuries [60, 65] or to assess the circulatory response in vascular diseases after the application of a cold stress [66, 67]. These tests commonly consisted of the application of cold local stress, such as the immersion of the extremities in cold water [60, 62, 65]. In these kinds of tests, the extremities are usually protected with plastic bags or gloves during the immersion [60, 62, 65–67], in order to prevent

(a) No training intervention



(b) Hypoxic training intervention

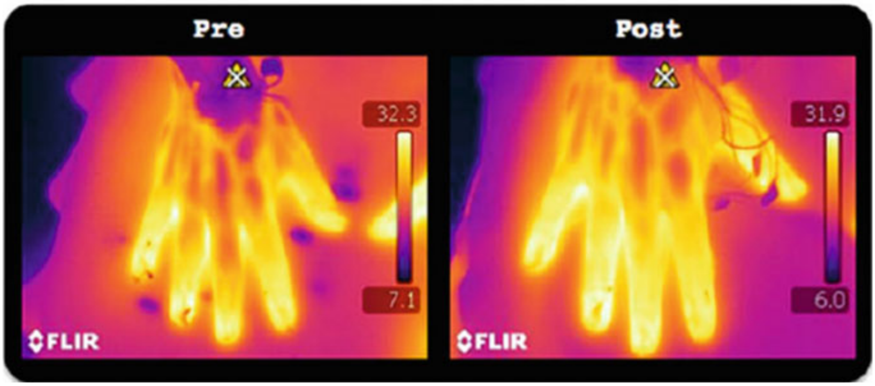


Fig. 12.9 Examples of thermographies before and after cold stress (immersion in water) in one participant without previous training (**a**) and another who had undergone a 10-day hypoxic training. Figure modified from Keramidas et al. [62]

skin wetting and subsequent evaporation and cooling, as well as the effect of water on the skin on temperature estimation, as was discussed previously. However, during all the tests, environmental conditions were moderate (~20 °C) and there is nor much research simulating real cold environments. Furthermore, infrared thermography can be a useful tool to assess the thermoregulatory capacity of athletes before mountain or winter sports in cold environments, in order to improve performance and reduce the cold injury risk. Studies to assess its benefits in this kind of application are necessary.

On the other hand, in the exposure of the warm environment, the objective of human thermoregulation is heat dissipation, mainly by two mechanisms: cutaneous vasodilation and sweat evaporation [5, 59]. Research in hot environments in sport science has the main objective of simulating exercise in conditions where the thermal stress is very high, and the risk of heat exhaustion and heat stroke is increased [10, 11, 68]. However, during room time adaptation in thermography studies, if sweat rate is very high, it could affect the thermal measurements, as was discussed previously.

In both cold and heat exposure research, the adaptations of the participants due to possible acclimatization to these environments may affect their thermoregulatory response [59, 69, 70]. In addition, if this response differs between participants, it will increase the thermal variability of the study. A methodological solution may be to make a prior period of acclimatization (between 6 and 10 days) at these temperatures for all participants. It is also important to consider that the room time adaptation before thermography measurements must be greater than that under a moderate environment [56, 71].

12.7 Skin Temperature Variables

Different descriptive statistics variables can be extracted from the thermal analysis. These variables are used by different studies: the average temperature of the ROI [2, 3, 31, 41, 72], the maximum temperature of the ROI [73–75], thermal asymmetry index of the ROI (difference between on ROI and its contralateral) [76–78], difference between one ROI that is a reference and the specific ROI [79, 80], and temperature variation (difference between during-after exercise and before) [38, 53, 54]. These variables are described in Chap. 3 of this book.

In each study, the variables of interest are selected for analysis. Furthermore, there is some knowledge about the applicability of some of the variables. For example, the thermal symmetry index is known to be useful for injury assessment [1, 77]. Temperature variation has been suggested to be a more valid measure than absolute temperatures to determine the effect of exercise [38, 53, 54]. However, more studies are necessary in order to highlight which method is the most indicated in each situation. For example, the maximum temperature of the ROI is one variable used by different studies [73–75], but its advantages compared with the average temperature are not clear. On the other hand, other variables such as the standard deviation of the ROI are not being used in sports science research. Standard deviation may be an interesting variable for exploring the presence of hot spots in one ROI and research is needed to investigate its application.

On the other hand, **body fat tissue** had an insulation capacity resulting in impairment in heat dissipation between the core and the skin [3, 81, 82]. This effect of body fat tissue resulted in lower temperatures or lower variation of the skin temperature during exercise [3, 42, 82] (Fig. 12.10). For this reason, for some studies it could be interesting to normalize the skin temperature by the fat tissue. However, more research is necessary to explore how to do this normalization. Nevertheless, the quantity of body fat tissue depends on the fitness level of the person [83] and, for this reason, it would not be recommended to normalize the skin temperature by the fat tissue in studies in which the objective is to assess the effect of fitness on thermoregulation [42].

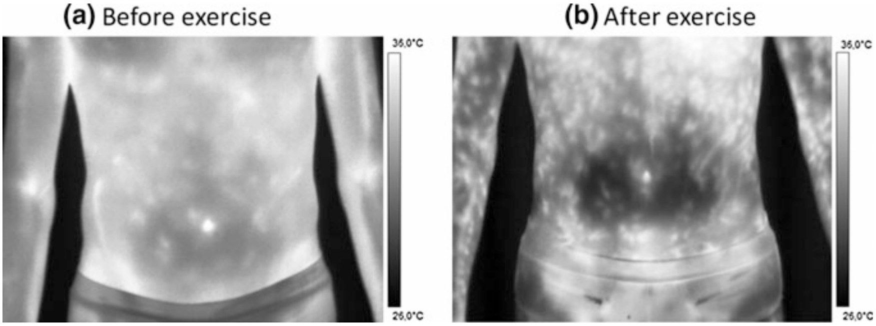


Fig. 12.10 Example of the lower skin temperature in the abdomen due to the effect of the fat tissue in this area, before (**a**) and after cycling for 45 min (**b**)

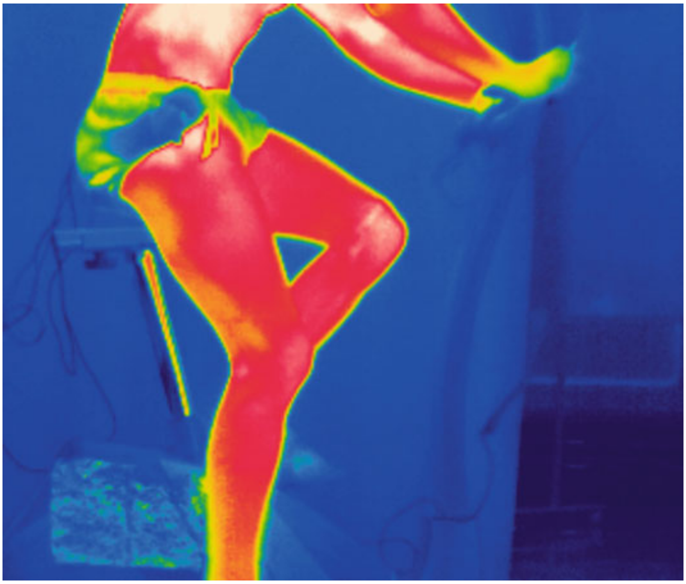


Fig. 12.11 Example of an image obtained from a video recording during cycling using a mechanic cycloergometer but with some computers and electronics systems close to the participant

12.8 Measuring During Exercise Versus Measuring Immediately After Exercise

Different studies have measured the skin temperature before and after exercise, and not during exercise [3, 38, 43, 49]. One of the main reasons to not measure during exercise is due to the recommendation that electronic equipment must be located away from the patient area in order to avoid disturbance in temperature reading [4, 84]. However, measures during exercise could provide valuable information and a more realistic scenario (Fig. 12.11). In this sense, there are a lack of studies concerning the effects of the radiation of this equipment on skin temperature. It is important that research attempts to quantify the effect of this equipment on the measurement; whether it is possible to omit this error; whether it is perhaps not possible to perform this kind of measure because the effect is so large; or, finally, whether it is possible to make some kind of correction to remove this calculation error.

12.9 Measuring Skin Temperature Recovery?

Physical exercise at a high intensity or/and for a long duration can lead to high core temperature, muscle damage, DNA damage and oxidative stress [10, 85, 86]. After exercise, it is necessary to restitute core temperature to basal values [87]. Vasodilation is one of the main mechanisms to dissipate the heat from the core to the skin [88]. Furthermore, glycogen resynthesis or muscle hypertrophy are also mechanisms that could alter the skin temperature [22, 89, 90].

In this vein, different studies have suggested that the assessment of skin temperature variation in the post-exercise period may be useful for understanding the human recovery process [22, 91, 92]. Al-Nakhli et al. found an increase in the skin temperature of the exercised arms 24 h after exercise [91]. They also observed a correlation between skin temperature and the delayed onset muscle soreness and suggested that the skin temperature was influenced by the hemodynamic variations in the recovery process [91]. Similarly, Neves and colleagues observed a skin temperature increase in arms immediately, 48, 72 and 96 h after strength training [92]. The results of the study suggested that this increment in skin temperature was related to the muscle volume increase, the inflammatory process and the tissue reparation. Finally, Fernández-Cuevas et al. observed that there is a progressive increase of the skin temperature up to 6 h after exercise [22].

Despite these interesting results, most of the research studies only analyzed the skin temperature immediately after exercise [31, 72, 76], or some short period (5–10 min) after the exercise was finished [2, 3, 29, 30, 38, 41, 54]. However, 10 min may not be enough to test the recovery process of skin temperature [93]. Further studies are necessary to assess the usefulness of analyzing skin temperature in the recovery process. It is possible that this application of the infrared thermography in sports science could be interesting for obtaining information about the assimilation of training loads, and provide data to answer whether the recovery process was sufficient and the athlete is able to start training again [22]. Furthermore, the recovery skin temperature assessment could help the staff of the sport teams to monitor their athletes, resulting in an improvement of the training management [22].

12.10 Skin Temperature Data Reference Need

The idea that there is a necessity for a database of thermal images or reference values of skin temperature normality has been suggested by different authors [20, 75, 94–96]. The establishment of a skin temperature reference may help to identify hyperthermic or hypothermic areas, and to easily detect some injuries or pathologies [75, 95]. With this clinical perspective, it is easy to understand why the idea to have a standard reference values is important in the medical area.

Different researchers have worked on the development of a basal thermography database. Fujimasa developed a database in 1997 with more than 20,000 binary thermal images [94]. Although the database developed was implemented in a website, this website currently seems to have ceased to be operational. Furthermore, some studies were oriented to establish normal thermal profiles for Brazilian adults [95], Polish physically active young people [97], obese women [82] and soccer players [75]. Thermal symmetry was also assessed to establish a reference value of 0.5 °C with a standard deviation of 0.3 °C [77]. There remains a necessity for reference values for medicine to be obtained [96]. Likewise, it would be interesting to establish a database for reference values that were more oriented to sports science; for example, from reference values of temperature variations produced by exercise.

For an appropriate comparison with the reference values, it is important to have data for all the body areas and for each population group (data differentiated by age, sex, anthropometry, etc.) [20, 75, 95]. Furthermore, there are some environmental and methodological conditions that could alter the skin temperature that are important to take into account: room temperature, relativity humidity, body posture, time of day, etc. For medical purposes, it is also important to have data for the different pathologies. Reference values of excellent quality should be classified, taking into account all these parameters. For a sports science purpose, we need also to know reference temperature values after exercise, during exercise, and temperature variations. Reference values of excellent quality for sports science should be classified by physical fitness level, and should take into account additional information related to the exercise: type, duration, intensity, wind speed, etc.

After all this information, it is easy to understand that obtaining a skin temperature database is complicated for basal values, and the degree of complexity increases when we think about obtain reference values related to exercise. Instead of performing singular studies that attempt to create such databases, it may be a more accurate methodology to obtain these reference values through the use of big data analysis, by grouping all of the published studies. For sports science, because the publication of thermographic studies in this area is fairly recent, it may be necessary to wait a few years before applying this methodology.

12.11 Conclusions

In this chapter, we tried to present our desires in relation to future research and developments of infrared thermography in sports science. Some of these desires are possible and perhaps others are unlikely to develop. However, it is believed that these ideas could help to guide researchers and manufacturers. In order to summarize the chapter, below are the aspects that we believe should be addressed in the future R&D in sports science:

- Increase the accuracy of infrared cameras with an accessible price.
- Develop thermography software packages that are more orientated to solving the issues of sport science assessment.
- Research more about the reproducibility of thermal data during and after exercise.
- Know how to deal with sweat in thermography exercise studies.
- Analyze the application of infrared thermography as a tool in the assessment of the thermoregulatory capacity of athletes before mountain or winter sports in cold environments.
- Research which skin temperature variable is most indicated in each situation.
- Know the effect of the electronic equipment on the measurements during exercise.
- Research more about the assessment of the recovery process after exercise.
- Develop a reference/database values of skin temperature for basal and exercise intervention.

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Editors' Conclusion

After reviewing all the chapters that are included in this book and considering the experience in developing research using infrared thermography in sport science, the editor would like to share a final conclusion related to the content of this book.

In general, we can see that there is an increase in interest among researchers for the application of infrared thermography in sport science. This fact is very well exemplified by Fig. 1.11, which shows the number of publications from its beginning in 1975 up to 2015. Furthermore, it can be considered that the most studied application has been the use of infrared thermography in sport medicine, and the assessment of human thermoregulation during exercise. However, although the number of papers is lower in other topics, such as clothing assessment or the application in animal sports (e.g., equestrian sport), it is important not to underestimate these fields of application where infrared thermography can have excellent applicability.

Although infrared thermography is a technique that seems easy to use, it is important to have the essential knowledge before its use. Knowledge about physical principles of infrared thermography, heat transference and thermoregulation are necessary in order to understand the operation of the infrared camera, to avoid and to know methodological issues, to establish logical hypotheses, and to correctly interpret the thermal results. Furthermore, valid measurement in thermography requires following strict methodological steps in order obtain accurate data.

However, more research is needed to determine the adequate procedures for data acquisition and analysis of infrared thermography. One of the most commented upon issues in this book—and it is a special concern for the editor and other infrared thermography users—is the effect of sweat in the estimation of skin temperature. To date, there is not the necessary evidence to determine the effect or error that may be produced by sweat in measuring skin temperature. It is critical to know this effect in order to determine whether we can measure sweaty skin, or whether sweat should be removed before taking any measurements.

Most of the thermoregulatory studies conducted during exercise have been performed using thermal contact sensors such as thermocouples. Differences between infrared thermography and thermal contact sensors are important to take into account before a study, in order to select the most appropriate technique.

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Infrared thermography could provide the measurement of large areas without interfering in the heat exchange of the athlete. However, it is not possible to take measurements when the subjects are clothed and the sweat could interfere in the temperature calculation.

On the other hand, there is a large heterogeneity of the skin temperature dynamics in the different studies. There is because skin temperature has a multi-factorial dependence and it is influenced by different factors such as the exercise characteristics, the environmental conditions, the other thermoregulatory variables (such as core temperature, sweat rate or blood flow) and the individual characteristics (sex, age, anthropometry and body composition, etc.).

The different chapters of this book showed that there is a large body of evidence for the applicability of infrared thermography in several fields of sport science. Infrared thermography is useful in the monitoring and prevention of injuries in sport medicine. It can provide valuable information for the clothing and equipment design and assessment. In addition, it presents a broad range of applications in equestrian sport as a complementary diagnostic tool in veterinary practice and sport performance.

In other fields, such as foot temperature assessment during exercise or psychophysiology, there is a lack of studies and its current use is minimal. However, the different chapters showed excellently the great potential for infrared thermography in these fields. The applicability of infrared thermography in sport science is constantly evolving and research is currently being performed to assess these potential fields. Clearly, in future editions of this book, these chapters should be updated, showing new evidence, and newly discovered applications.

Although infrared thermography began its use in sport science approximately 40 years ago, we can consider that its use in research laboratories has been extended in recent years, while still a fairly new technique in sport science compared with other instruments such as the electromyography, the photogrammetry or the indirect calorimetry. For this reason, more research is necessary to improve all the research phases: the methodology, the image acquisition, the data analysis, and the interpretation of the results.

Finally, a more effective approach between the laboratory and the field is necessary. Infrared thermography is starting to be used in some high level sport clubs in order to reduce the number of injuries through the daily monitoring of their athletes. However, despite its important benefits in this field, its extension to date is minimal and it is hoped that in the future there will be a higher number of sports clubs and sports associations. On the other hand, other applications are not being used in the field (e.g., psychophysiology). Therefore, it is necessary to establish a real and effective bridge between research and sport centers in order to ensure that all the effort from the research laboratories is being effectively transferred to the field, with the aim of improving performance and reducing injury risk through the use of infrared thermography.

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