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Review

Determination of Thermal Comfort in Indoor Sport Facilities Located in Moderate Environments: An Overview

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Abstract: In previous years, providing comfort in indoor environments has become a major question for researchers. Thus, indoor environmental quality (IEQ)—concerning the aspects of air quality, thermal comfort, visual and acoustical quality—assumed a crucial role. Considering sport facilities, the evaluation of the thermal environment is one of the main issues that should be faced, as it may interfere with athletes' performance and health. Thus, the necessity of a review comprehending the existing knowledge regarding the evaluation of the thermal environment and its application to sport facilities becomes increasingly relevant. This paper has the purpose to consolidate the aspects related to thermal comfort and their application to sport practice, through a deep study concerning the engineering, physiological, and psychological approaches to thermal comfort, a review of the main standards on the topic and an analysis of the methodologies and the models used by researchers to determine the thermal sensation of sport facilities' occupants. Therefore, this review provides the basis for future research on the determination of thermal comfort in indoor sport facilities located in moderate environments.

Keywords: thermal comfort models; thermal comfort assessment; Fanger's models; moderate environments; sport facilities

1. Introduction

In recent years, ensuring comfort in indoor environments has become a real challenge involving different disciplines. However, in the past, the parameters used to guarantee comfort and the approaches to improve the quality of the indoor environment were often studied separately [1]. Furthermore, comfort in indoor spaces can be ensured through the control of all the environmental factors, which include indoor air quality, thermal comfort, lighting, and acoustical quality [2]. In this context, the indoor environmental quality (IEQ) that includes all these aspects, assumes a fundamental role in the determination of the conditions of comfort in buildings. Since the time that humans spend indoors has largely increased, several studies have been carried out in order to enhance comfort in indoor spaces, especially in offices, schools, hospitals, etc. The focus of researchers was often based on possible improvements of air quality [3] or on the reduction of the impact of pollutants in indoor air [4]. Visual quality and acoustical comfort have been also studied in workplaces and in educational rooms [5–8], since they may have a great impact on the focus and on the performance of the occupants. Finally, thermal comfort has been often studied in relation to the characteristic of the envelope and of the internal structures [9], as the thermal behavior of the building can largely influence the environmental conditions indoors, which also has an impact on the comfort and performance of people.

In sport facilities, these four aspects have been studied in order to improve the comfort and the performance of the athletes. In particular, light has been recognized as one of the most important factors to ensure the correct practice of the sport [10,11], while indoor air quality has been considered fundamental for ensuring health of the athletes [12]. Then, since swimming pools and sport halls are environments in which noise level and speech intelligibility can determine the comfort or the safety of the occupants, research on the assessment of acoustic conditions and on the use of acoustic treatments to improve the quality of the environment have been carried out [13].

The thermal environment is probably the most important parameter that should be considered when performing sports, as it can determine the safety and the performance of the athletes. In moderate environments, defined as spaces in which it is possible to reach the condition of thermal well-being, only few studies have been carried out. These studies were focused on the monitoring the thermal conditions according to thermal comfort indices [14,15], on the interventions to improve thermal comfort [16,17], on the comparison between objective and subjective measurements [18,19], on the assessment of thermal comfort to balance energy use [16,20] and on the association between thermal comfort and physiological responses during exercise [21,22]. However, there was no standardization in the measurement methodologies or in the models that were used to predict thermal sensation in sport facilities. Even the norms regarding the perception of the thermal environment do not often consider the parameters that should be maintained in sport halls and swimming pools and only in some cases Sports Federations provide these values, even if they are often incomplete.

The main purpose of this article is to consolidate the existing knowledge regarding the thermal environment and its application to sport facilities. In order to achieve this result, it was necessary to use a multidisciplinary approach that considers all the aspects of thermal comfort, from the engineering approach, which treats man as a heat engine, to the physiological and psychological ones, which also play a key role in the perception of the thermal environment, especially during sport practice. Then, in order to consider the practical aspects of the prediction of the thermal sensation of the athletes, the main standards and Federations' norms have been reviewed, as well as the models used by researchers to evaluate thermal comfort in sport facilities. Finally, the methodologies developed to assess thermal comfort in these environments have been studied. This paper lays the groundwork for future research on the determination of indoor thermal comfort in sport facilities located in moderate environments, as in these spaces thermal conditions have a fundamental role in the performance and in the health of the athletes.

2. Thermal Comfort Approaches

The perception of the thermal environment can be considered dependent on several factors, derived from different fields of research. In particular, three main approaches have been identified: engineering, physiological, and psychological approaches. The engineering approach is based on the representation of the humans as 'heat engines', who can exchange heat with the environment and it implies that the thermal sensation is dependent on the heat balance of the human body. The physiological approach considers instead the mechanisms with which the body responds to the thermal environment (e.g., thermoregulatory responses). Finally, the psychological approach concerns the psychological phenomena regarding the individuals' perception of a certain environment [23].

2.1. Engineering Approach

In the engineering approach, the human body is represented as a heat engine, which can give or receive heat from the environment through conduction, convection, radiation, and evaporation. The heat in the body is produced by the metabolic processes occurring during human life. The heat exchange between the body and the environment can be determined through the heat balance equation [23]

$$M - W = C_k + C + R + E + S \tag{1}$$

where M is the metabolic rate of the body (W), W is the mechanical work (W), C_k is the heat transfer by conduction (W), C is the heat transfer by convection (W), R is the heat transfer by radiation (W), E is the heat transfer by evaporation (W), and S is the heat storage (W).

In conditions of thermal equilibrium, the heat storage is null (S = 0) and the heat balance equation can be written as

$$M - W - C_k - C - R - E = 0 \tag{2}$$

Note that this equation is generally applied to steady state conditions and it should be carefully adopted during sport practice, as exercise is usually performed under transient conditions. Figure 1 reports the mechanisms of heat transfer during exercise.

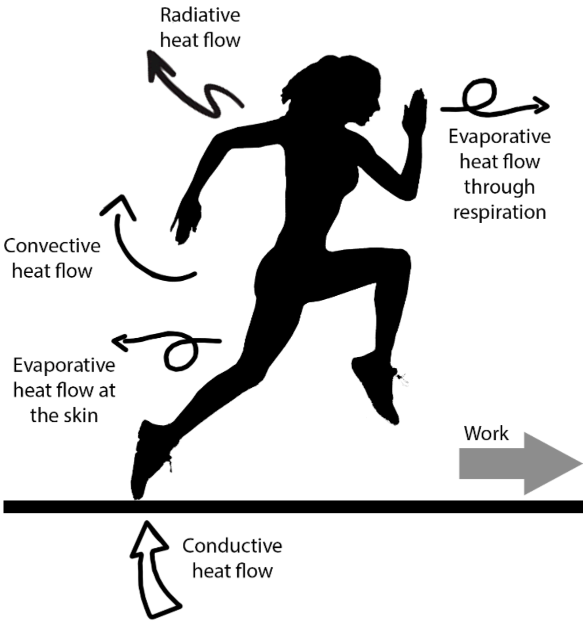


Figure 1. Heat transfer mechanisms during sport activity. The body can exchange heat with the environment through conduction, convection, radiation, and evaporation. The production of external work through muscular activity leads to an increase of the heat that has to be dispersed in the environment.

2.1.1. DuBois Area

The heat produced by the body flows through the body surface. A method for the calculation of the nude body surface area is given by DuBois formula [24]

$$A_{DB} = 0.2025\ W^{0.425}\ H^{0.725}, \tag{3}$$

where W is the weight (kg) and H is the height (m) of the body. Generally, the value of $A_{DB} = 1.8\ m^2$ is assumed.

2.1.2. Heat Exchange through Conduction

Generally, the heat exchange between the body and the environment through conduction is limited, as it involves small parts of the body. Therefore, the conductive effects are often neglected, or included in the convective effects [25]. However, conduction must be considered in the heat balance when the body is in contact with large surfaces. In this case, the heat loss or gain is dependent on factors such as the body and surface temperatures, the area of contact and the conductivity of the surface and of the body tissues [26]. During sport activity, heat exchange through conduction can occur for example in running, when the athlete is running on a hot road, or in cycling, when the athlete is in contact with the seat of the ridden bicycle.

2.1.3. Heat Exchange through Convection

Heat transfer through convection totals up to 15% of the whole heat loss in stationary conditions, but even more when the air is moving over the body surface [26]. During sport activity, convection can occur due to the body movement, which generates air (e.g., in running, riding, etc.) or water (e.g., swimming) currents or due to the air movement (e.g., wind). The air movement around the skin is responsible for convective cooling.

Heat transfer by convection is given by [25]

$$C = h_c\ (T_{sk} - T_a)\ A_c\ f_{cl}, \tag{4}$$

where h_c is the convective heat transfer coefficient (W/m^2 K), T_a is the air temperature (K), T_{sk} is the mean skin temperature (K), A_c is the body surface involved in the heat exchange through convection (m^2) ($A_c \approx A_{DB}$) and f_{cl} is the clothing area factor.

The clothing area factor (f_{cl}) can be calculated as [27]

$$f_{cl} = 1.00 + 0.28\ I_{cl}, \tag{5}$$

where I_{cl} (clo) is the thermal insulation of clothing, whose values are provided for everyday garments in the tables reported in the ISO 9920. Movement tends to let the insulating characteristics of the clothing and of the boundary air layer decrease. In warm environments, where convective heat loss has a positive effect, fabrics are developed in order to let the air to flow between the body and the garments. Conversely, in cold environments, clothing is designed in order to minimize the air movement, preventing convective heat transfer and maintaining body warmth [28].

The convective heat transfer coefficient (h_c) is a function of several parameters such as the velocity of the currents, density, and viscosity of the fluid involved and the shape of the exposed surface. An approximate value of h_c is given by [25]

$$\begin{aligned} h_c &= 3.5 + 5.2\ V_{ar}, && \text{for } V_a \leq 1\ \text{m/s} \\ h_c &= 8.7\ V_{ar}^{0.6}, && \text{for } V_a > 1\ \text{m/s} \end{aligned} \tag{6}$$

where V_a is the air velocity (m/s), V_{ar} is the resultant air velocity (m/s) considering the environmental air velocity and the movement of the person and it can be calculated as [25]

$$V_{ar} = V_a + 0.0052\ (M - 58), \tag{7}$$

where M is the metabolic heat production (W/m^2), with the condition that it is considered M = 200 W/m^2 when M exceeds the value of 200 W/m^2.

The influence of the human body's movement on heat exchange can be considered through the calculation of the convective heat transfer coefficient. Several studies have been carried out on this topic, analyzing standing and seating postures and different air speeds occurring due to the movements of mannequin simulating walking and running [29,30] or to the wind [31]. Further research has been developed using computational fluid dynamics to assess the convective heat transfer of individual body segments for cyclist positions [32]. Moreover—since water convection is the only important heat transfer mechanism—in the past, several studies have been performed in order to determine h_c analytically [33], or on a heated copper manikin located in the water [34], or detected on experimental data on humans [35].

2.1.4. Heat Exchange through Radiation

Thermal radiation is considered to be one of the factors that can influence the most the heat exchange during sport activity [26]. Only in water sports, the component of radiative heat loss is usually negligible [36]. Since body temperature during exercise is generally higher than the air temperature, there is a loss of radiative heat energy from the body. Only in warm environments, where the air temperature may be higher than the skin temperature, the body can gain heat through radiation.

The heat loss through radiation is given by [25]

$$R = h_r\ (T_{sk} - T_r)\ A_r\ f_{cl}, \tag{8}$$

where h_r is the radiative heat transfer coefficient (W/m^{2}K), T_r is the mean radiant temperature (K), T_{sk} is the mean skin temperature (K), A_r is the effective radiation area of the body (m^2) and f_{cl} is the clothing area factor.

h_r can be calculated as

$$h_r = 4\sigma\varepsilon_{sk}\left(\frac{T_r + T_{sk}}{2}\right)^3, \tag{9}$$

where $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4 is the Stefan-Boltzmann coefficient, ε is the emissivity of the body (for the skin ε = 0.97–0.98).

A_r, the effective radiation area of the body is given by [25]

$$A_r = (A_r/A_{DB})\ A_{DB}, \tag{10}$$

where A_r/A_{DB} = 0.67 (for squatting position)—0.70 (for sitting position)—0.77 (for standing position).

2.1.5. Heat Exchange through Evaporation

Heat loss through evaporation can occur through skin (by passive diffusion or sweating) and respiratory system (by breathing). Under steady state conditions, it accounts 10% to 25% of the total heat loss and it depends on factors such as relative humidity of the environment, air and skin temperature, air velocity, and clothing [37]. During sport activity, thermoregulation depends mainly on the heat loss through evaporation of sweat and it can arrive to account up to 90% of the total heat loss [38]. In water sports, evaporation cannot be considered as a mechanism of heat exchange [36].

Heat exchange through evaporation can be calculated as [25]

$$E = h_e\ (P_{skH2O} - P_{aH2O})\ A_e\ F_{pcl}, \tag{11}$$

where h_e is the evaporative heat transfer coefficient (W/m^2 Pa), P_{aH2O} is the water vapor pressure in the environment (Pa), P_{skH2O} is the water vapor pressure in saturated air at T_{sk} (Pa), A_e is the evaporative surface (m^2), and F_{pcl} is the clothing permeability factor.

h_e can be calculated as [25]

$$h_e = k\ h_c, \tag{12}$$

with k = 16.7 K/Pa

A_e can be calculated as

$$A_e = (A_e/A_{DB})\ A_{DB} = w\ A_{DB}, \tag{13}$$

where w is the skin wittedness, which is a physiological index defined as the ratio between the actual sweating rate and the maximum sweating rate that occurs when the skin is completely wet. w can range from 0.06, when the evaporative heat loss is caused only by passive diffusion, to 1, when the skin surface is completely wet.

2.1.6. Strategies Adopted from Athletes using Heat Transfer Mechanisms to Support Thermoregulation

The heat transfer mechanisms may support thermoregulation and improve sport performance [39]. Conduction is often used when an athlete is warm to decrease his body temperature. In particular, possible solutions are to put him in contact with cold surfaces or to let him wear special clothing such as ice vests. When the athlete is cold, wearing sport garments that present good thermal insulation may prevent the heat flow from the skin to the environment. In fact, conduction is particularly important when designing sport equipment, especially when it is composed by conductive materials, as for example the baseball bats or the motor racing seats. In this case, it is important to maintain the equipment at a temperature that is safe for the athletes.

Convection is an effective method to decrease body temperature and it can be supported by the use of fans that increase the heat flow and cool him down. On the contrary, the use of wind-breaker jackets may prevent excessive body cooling when the athlete is cold.

Heat loss through radiation can be increased by increasing the skin exposure to the environment or decreased by exposing the athlete to the sun or to other radiation sources.

Finally, evaporation is a fundamental heat transfer mechanism during exercise, as the body can produce a great amount of sweat. If an athlete is warm, pouring the water over the body can be an efficient way to decrease his temperature, as it leaves more water on the skin to evaporate. Conversely, if an athlete is cold, solutions to prevent the sweat evaporation include removing the water from the skin, removing wet clothes, or wearing additional clothes.

2.1.7. Use of Sport Garments to Control Heat Transfer Mechanisms

The presence of clothing on the human body has several implications on the heat balance. In particular, when considering sport garments, the selection of certain materials and design play a key role in the performance of the athletes. In particular, sport clothing must provide thermo-physiological comfort, supporting the wearer's thermoregulation, keeping the wearer at a comfortable temperature and maintaining the micro-climate between skin and textile as dry as possible [40]. For this reason, understanding the requirements of each sport is an essential step in the design of sport apparel and different studies have been performed for specific sports as for example baseball [41], snowboarding [42], rowing [43], athletics [44], or fitness [45]. The importance of sport clothing is evident when the protection from the environment is required for survival (e.g., mountain sports), but even in common applications it can have a fundamental role in athletes' performance. The aim of sports garments is in fact to provide a comfortable microclimate for the athletes, since comfort may affect their sport performance as it can avoid them from using more reserves in order to maintain the heat balance with the environment [46]. The aim of the study on sport garments is particularly relevant as, in some sports, a uniform is required (e.g., fencing), which does not allow the athletes to modify their conditions, and to adapt to the thermal environment.

The aspects that must be considered with regard to the thermal performance of clothing are the thermal and the moisture management. The early versions of performance garments consisted of a three-layer system, constructed with a base layer with the function of managing the moisture, a middle layer necessary for the insulation and a protective outer layer [47]. Even if this system was primarily used for outdoor apparel; nowadays, it is often adopted in the production of garments for indoor sports, with specific adaptations in order to improve performance. In fact, the necessities of the athletes may be different according to the environment in which they are exercising, as in moderate climates the heat production is high and heat generally flows from the body to the ambient, while in severe environments (both cold and hot) the mechanisms of heat exchange may be different. Moreover, professional athletes may have additional requirements for their apparel, as they have to exchange a great amount of heat with the environment, due to their high metabolic rates. For this reason, the composition of the garments is particularly relevant, as it can determine the heat exchange preventing the heat transfer by conduction, maintaining still air in the clothing, and managing moisture.

The mechanisms of heat transfer through clothing are shown in Figure 2. Regarding the heat exchange through conduction, the presence of garments on the body reduces the amount of heat loss and the characteristics of the clothing may affect the way in which the heat is exchanged [48]. Substantially, the heat transfer through conduction occurs between the inside and the outside of the clothing. In hot environments, apparel should be composed by high conductive materials, in order to let the heat flow from the body to the surroundings, while in cold conditions they should present low conductivity and they are required to have layer that can trap air, in order to improve their thermal resistance [28]. During sport activity, convection may occur between the apparel (or the skin) and the environment. In warm conditions, the main necessity is to cool down the body, therefore apparel is designed to allow the air flow between the body and the garments, while in cold environments the movement of air should be minimal [28]. Considering the sport of swimming, the optimization of the convective flux has not only the function of improving the heat exchange, but it can enhance the performance thanks to the better hydrodynamics [49]. With regard to the heat exchange through radiation, thermal insulation of the clothing can lead to a decrease of this heat flux, through the reduction of the temperature difference between the skin and the surrounding area. In particular, color and texture of sport clothing are specifically relevant to the heat gain and loss through radiation [28]. For this reason, several studies have been performed in order to produce clothing with metallic coatings or finishing technology that can shield infrared radiation [49]. Finally, since evaporative heat loss is specifically relevant during sport activity, it is important to take it into consideration when designing sport garments. In particular, in warm climates, clothing should be conceived to transport the sweat on their outer layer in order to let it evaporate, thus reducing the body temperature. In cold environments the athletes must also sweat, even if the evaporation of moisture is not intended, thus fibers that draw sweat to the outside of the apparel or to the internal microclimate of clothing are generally used [28].

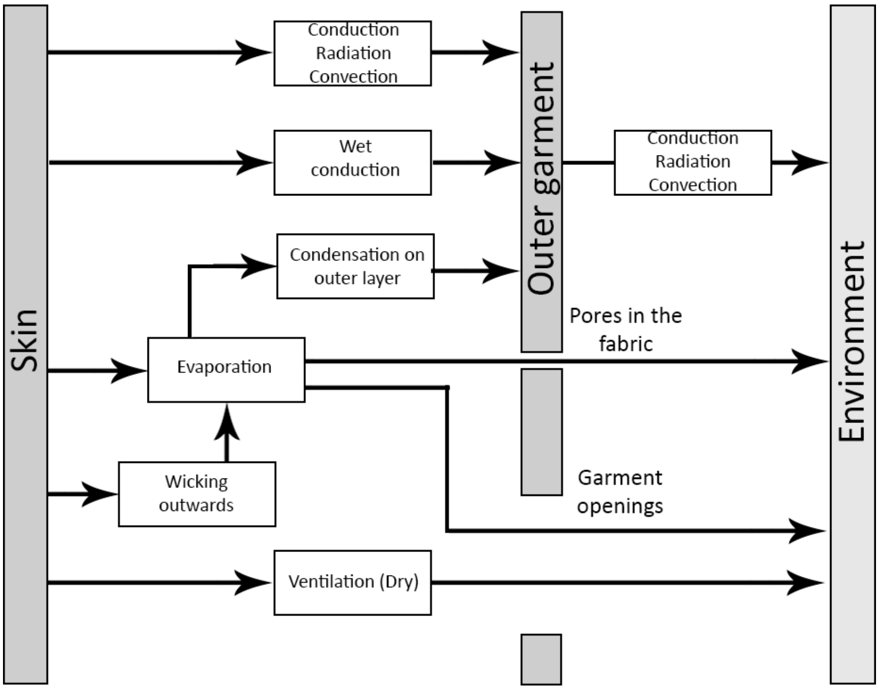


Figure 2. Heat transfer through clothing (modified from [50]). Heat flows from the internal to the external part of the clothing through conduction and then it is exchanged with the environment through conduction, convection, radiation, and evaporation.

2.2. *Physiological Approach*

The physiological approach concerns the mechanisms with which the body reacts to the thermal environment (e.g., thermoregulatory responses).

2.2.1. Heat Production during Exercise

The estimation of the heat produced by the metabolism is fundamental to assess the human thermal environment. The free energy necessary for living processes comes from the food and is then converted in the body cells thanks to the ATP-ADP cycle (adenosine triphosphate–adenosine diphosphate cycle) for ensuring life processes and for producing internal and external work. Internal mechanical work consists of the processes that take part in the body, such as the blood circulation, the movement of the air through the lungs or the work of the heart, while external mechanical work is a consequence of muscular contraction [51]. The metabolic heat is a waste product of the metabolism and it must be dispersed in the environment, in order to maintain the body temperature constant (Figure 3).

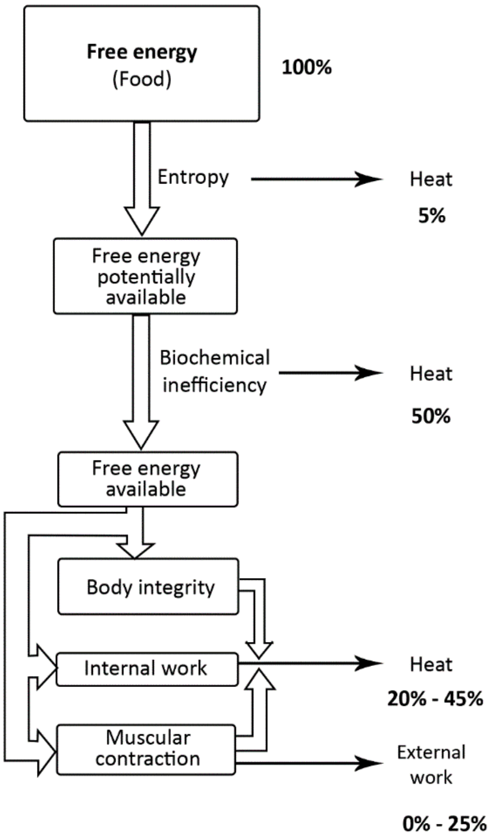


Figure 3. Transformation of free energy into work and heat (modified from [51]). The free energy coming from food is transformed into internal and external work and it is fundamental to guarantee body integrity. However, due to the inefficiency of the systems, part of the energy is converted into heat, which must be released in the environment.

The energy expenditure is distinguished in basal metabolism (at rest) and energy metabolism (when muscular work occurs). The basal metabolism is used for vital processes such as cerebral, circulatory, or respiratory activities and it is dependent on several factors—including sex, age, or hormonal activity—while the energy metabolism occurs during muscular work and it depends on the intensity of the work, the speed and the duration of the muscular contraction. The measurement of the metabolic activity is performed through the detection of the oxygen consumption. In particular, 1 l of O2 corresponds to 21.1 kJ if carbohydrates are oxidized or to 19.6 kJ if lipids are oxidized [51].

During sport activity, muscular contraction takes place thanks to the energy released by ATP. However, the ATP reserves are sufficient only for work lasting about one second. For this reason, the body presents some energetic mechanisms able to re-synthetize ATP. There are three main energy systems for ensuring these mechanisms [52]:

- anaerobic alactacid metabolism
- anaerobic lactacid metabolism
- aerobic metabolism

Of these, it is important to consider the power (maximum amount of energy produced), capacity (total amount of energy produced), latency (time necessary to obtain the maximum power), and resting time (time necessary for the reconstitution of the system). Table 1 shows the characteristics of each of these energy systems.

Table 1. Characteristics of the three energy systems to re-synthetize ATP.

	Anaerobic Alactacid Metabolism	Anaerobic Lactacid Metabolism	Aerobic Metabolism
Power	High (60–100 Kcal/min)	Medium (50 Kcal/min)	Low (20 Kcal/min)
Capacity	Very low (5–10 Kcal)	Medium (40 Kcal)	High (2000 Kcal)
Latency	Minimum	Medium (15–30 s)	High (2–3 min)
Resting time	Rapid	Subordinate to the elimination of lactic acid in the muscles	Long (36–48 h)

In general, these energy systems during sport activity do not occur separately, but they intervene together. As the number of sport activities is vast, it can be fundamental to describe the kind of mechanism occurring through the time necessary to perform certain movements (Table 2). For example, a basketball match has a duration of 40–48 min; therefore, considering what previously stated, it would mean that the metabolic system involved is the aerobic. However, in basketball rapid and intense movements occur, which involve also the anaerobic systems. Therefore, basketball and other sports such as fencing, baseball, football, golf, hockey, tennis, or volleyball involve both aerobic and anaerobic phases. In other sports such as swimming, running, skiing, or rowing, the energetic system used depends on the duration of the competition. For example, as swimming 200 m and running 800 m require the same time, the energetic system used by the body will be the same.

Table 2. Duration of the performance in relation to the energy system (modified from [52]).

Time	Energy System	Sport
Less than 30 s	Anaerobic alactacid	Running 100 m
30–90 s	Anaerobic alactacid + lactacid	Running 200–400 m, swimming 100 m, skating
90 s–3 min	Anaerobic lactacid + Aerobic	Running 800 m, combat sports (2–3 min matches)
Over 3 min	Aerobic	Marathon, jogging, cross-country skiing

The measurement unit of the metabolic rate is the Met; 1 Met corresponds to the metabolic rate at rest.

$$1 \text{ Met} = 58 \text{ W/m}^2$$

Standards report the metabolic rate for different activities and the way in which they can be calculated [53] while the 2011 Compendium of Physical Activities [54] shows the metabolic rate for different sports. Table 3 displays the metabolic rate corresponding to different activities.

Table 3. Typical metabolic rates for different activities (modified from [54]).

Activity	Metabolic Rate (Met)
Resting	
Sleeping	0.8
Seating, quiet	1.0
Standing, relaxed	1.2
Sport and Activities	
Archery	4.3
Badminton	5.5
Basketball	8.0
Bicycling	7.5
Boxing	12.8
Calisthenics	3.5
Dancing	7.8
Fencing	6.0
Fishing	3.5
Football	8.0
Gymnastics	3.8
Hockey	8.0
Running	7.0
Skiing	7.0
Swimming	4.8–13.8
Tennis	7.3
Volleyball	4.0

2.2.2. Thermoregulation during Exercise

In humans, temperature is regulated through control systems that ensure homeostasis through behavioral and physiological mechanisms of thermoregulation. The first includes all the tools that humans can use to support their thermal comfort, such as the choice of an appropriate clothing or the adjustment of the indoor environmental conditions (opening/closing a window, use HVAC systems, etc.). The second consists of several physiological mechanisms which can intervene to maintain homeostasis, which are the vasomotor response (vasoconstriction or vasodilation), sweating, and shivering. The physiological thermoregulation is a feedback system: temperature receptors are located in the skin and they are connected to the hypothalamus, which has the function of providing homothermia and can activate the mechanisms of thermoregulation through nervous pathways (Figure 4). The physiological field of thermoregulation is generally wider than the zone of thermal neutrality which also represents the zone of thermal comfort. Therefore, behavioral thermoregulation occurs earlier than physiological thermoregulation.

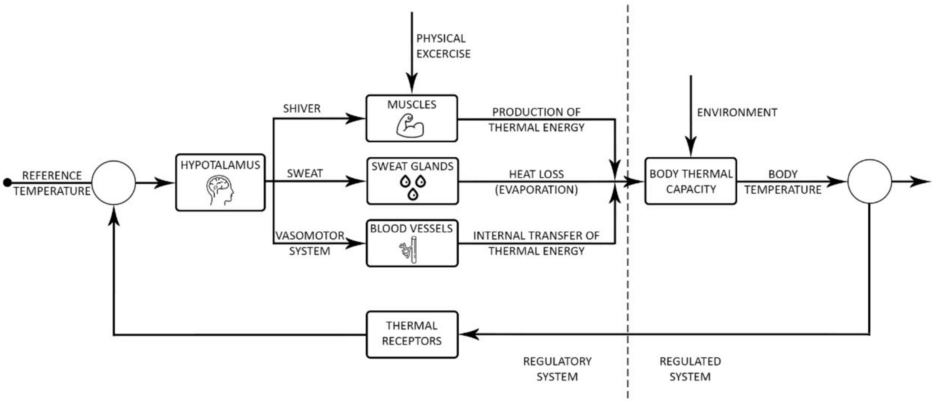


Figure 4. Human thermoregulatory system (modified from [55]). Temperature receptors located in the skin are connected with the hypothalamus, which compares the temperature of the body with a reference temperature and it can activate thermoregulatory systems in order to maintain body temperature constant.

During sport practice, the heat production of the body may exceed 1000 W, thus the body temperature tends to increase. In fact, only a modest part of the heat produced by muscles is initially transferred to the environment and most of it increases body's internal temperature. For example, it has been demonstrated that during intense cycle exercise, the temperature can rise up to 1 °C/min [56]. This heat storage cannot be maintained for long periods, or the athletic performance would be compromised due to the overheating and heat exhaustion. When the temperature reaches a certain limit, the thermoregulatory systems occur and the heat is dissipated though vasodilation and sweat. These mechanisms do not occur only in warm environments, but in every condition when the physical exercise is intense enough. In fact, muscular usage generally increases body temperature, usually resulting in temperatures higher than the environmental temperature.

Training can improve thermoregulation during sport practice, leading to an increase of sweat rate and skin blood flow. In fact, elite performers usually present an augmented sweat secretion that occurs in the early phase of exercise, leading indeed to a fast dehydration. Furthermore, professional athletes show an increase of blood total volume and maximal cardiac output, resulting in a better heat dissipation through vasodilation that leads the temperature decrease thanks to the convective cooling [57]. Acclimatization plays also a crucial role in sport performance, especially when competitions take place in different environments from where athletes are used to train.

Gender and age differences can also play a key role in thermoregulation, since physiological properties (e.g., sex hormones, exercise capacity, etc.), anthropometric characteristics (e.g., body mass and size), body composition (e.g., muscles and body fat), and physical activity level may be different. In general, women and elderly people have a lower sweat capacity and a higher core temperature than men [58] and therefore they present less endurance because of heat exposure. Actually, it has been observed that the human response to exercise depends mostly on the aerobic capacity (VO_{2max}), which is also correlated to factors such as gender and age [59].

Finally, another aspect that may affect thermoregulation is clothing, as it represents an additional layer that may delay the heat transmission through conduction or prevent the sweat evaporation. However, research has shown that in warm and in moderate environments, garments do not have any effect on the thermoregulatory response. In fact, the addition of layers or the fabric characteristics seem not to affect the physiological responses of the body [60]. On the contrary, in cold conditions clothing may influence thermoregulation and in this case the ideal clothing can block air movement but allows the passage of water vapor when the production of sweat occurs [61].

2.2.3. Body Temperature during Exercise

The human body can be considered divided in two parts, a core (inner part) and a shell (outer part). The temperature of the central core in stationary conditions is maintained stable by the thermoregulatory systems activated by the hypothalamus that maintains homeostasis, as the internal temperature cannot exceed certain limits, or the vital organs would result compromised. The shell temperature is usually defined by the mean temperature on the skin and it can vary according to the environmental conditions. The variation of the body temperature depends on several factors such as the environmental conditions, the thermoregulatory system and the metabolic rate, which determine the heat production of the body. During sport activity, the core temperature can rise up to 40 °C, due to muscular strain which determines a large amount of metabolic heat production. Temperatures higher than 40 °C may cause performance break-down or, in extreme cases, health problems [62]. Skin temperature has instead a different trend that it is usually inversely proportional to the exercise intensity, at least at the onset of exercise [63]. Recent studies on runners showed that in the first phase of exercise the body presents a decrease of skin temperature due to the vasoconstriction while, as soon as the core temperature reaches the threshold values, the warmer blood is directed to the shell, leading to an increase of skin temperature and to a decrease of core temperature [64]. However, since different sports involve the use of specific muscles, in the non-active regions the skin vasoconstriction is particularly evident, while in the active ones the skin temperature increases earlier due to the thermal conduction from the active muscles to the skin surface above them [65].

The evaluation of body temperature during exercise is fundamental to ensure a good performance and healthy conditions to the athletes. In extreme cases, when the body temperature gets too high (hyperthermia) or too low (hypothermia), accidents may occur, as it can happen in warm and humid environments or in cold spaces. Warm and humid environments are particularly critical for athletes [52], since their thermoregulatory system cannot properly operate (high temperature prevents heat transfer by convection and radiation and high humidity levels do not allow the sweat evaporation). For this reason, the assessment and the control of core and skin temperatures have a primary importance in the performance and in the safety of the athletes.

2.3. Psychological Approach

The thermal sensation perceived by humans derives from the sensory experience, therefore it cannot be based only on physical or physiological approaches. In fact, often the environmental factors are not always the cause of thermal dissatisfaction in buildings [66]. Even people's expectations may influence their satisfaction, as occupants can be satisfied with a certain environment because they do not expect any better condition, or be dissatisfied because they would expect a different environment. For example, elite athletes may have different expectation than other athletes, as they are more used to high quality environmental conditions. Thus, a certain environment could be considered satisfactory or not according to the personal experience of the single athlete and not for the physiological or environmental conditions.

2.3.1. Thermal Sensation

Thermal sensation is related to physical and physiological aspects, but also to psychological features, as it is related to how humans feel in a certain environment. It is important to distinguish how a person feels and how he or she would like to be (warmer/colder) or how a certain environment can be described. In particular, physical exercise can affect the thermal response of the athletes, as they may feel warm in environments in which they would perceive cold feelings in conditions of rest. The research of McIntyre [67] shows that usually cold sensations are determined by mean skin temperature, while warm feelings occur initially due to skin temperature and then due to core temperature and they are closely related to the skin wettedness. Furthermore, it has been demonstrated [68] that skin temperature, which may affect the thermal sensation of the athletes, is closely related to environmental conditions for a large range of exercise (from 30% to 70% VO_{2max}). Acclimatization can also play a fundamental role in the perception of the thermal environment, reducing the warmth sensation up to 70–80% during sport practice where air temperature was maintained 50 °C [68].

2.3.2. Thermal Discomfort

Thermal discomfort during exercise has an important role in sport performance, since it may affect the sense of effort of the athletes. Warm discomfort appears when physiological mechanisms such as vasodilation and sweat secretion occur, but it is also dependent on factors like body temperature and skin wittedness [69]. In particular, it was shown that during exercise in thermal equilibrium the level of skin wittedness providing a sensation of comfort rises from 0–10% to 20–25%, showing the influence of physical activity on human feelings. Moreover, when considering steady-state exercise, warm sensations are generally reduced when the athletes are well trained; otherwise, thermal discomfort was usually associated with the sweat rate and to the vasomotor response [68]. On the contrary, cold discomfort occurs due to vasoconstriction and to the consequent reduction of skin temperature [69]. However, this situation is generally related to sport practice in cold environments, since the majority of heat produced by the body during exercise leads usually to warm sensations.

3. Standards

Thermal environments are divided into moderate, hot, and cold. For moderate environments, the reference standard is the UNI EN ISO 7730 [70], which reports the indices that can be used to evaluate the perception of the thermal environment in indoor spaces. Furthermore, general standards explain the main concepts regarding the thermal environment, including the calculation of clothing insulation, the assessment of metabolic rate for different activities, the methods to conduct objective, and subjective measurements and the explanation of the physiological responses of humans. Figure 5 shows an overview on the current normative regarding thermal comfort, even if there is to consider that in this field, the normative is continuously evolving, as technical and scientific knowledge is rapidly developing.

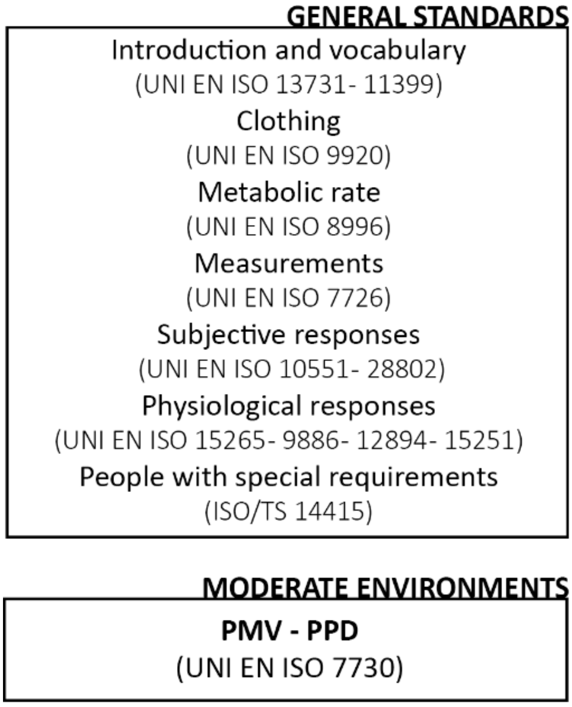


Figure 5. Standards for thermal environments: an overview (modified from: [55]). General standards can be applied to all environmental conditions, while the others can be used for the calculation of specific indices developed for different thermal environments.

With regard to sport facilities, generally they can be very heterogeneous, therefore specific literature and standards for the regulation of the parameters that should be maintained in these environments are needed. In fact, often different activities are carried out in these spaces as they are usually multifunctional buildings in which diverse sports are performed, hence the difficulty of finding a unique norm that handles all these aspects. Since the legislation regarding construction and maintenance of sport facilities is often related to hygienic conditions, the normative varies among countries. For example, in the USA the first standard concerning the thermal aspects in indoor environments is the ASHRAE 55/2004, regarding "Thermal Environmental Conditions for Human Occupancy" [71]. However, this standard does not provide any specific value to be maintained in sport facilities and usually different States present diverse regulations on these aspects. In Russia, the SNIP 31-112-2004 "Physical Training and Sports Halls" [72] reports the values of air temperature, relative humidity, and air velocity that should be maintained in an "ordinary sports hall", where different activities can be carried out. Therefore, this standard does not provide any specific information regarding the values to be maintained in different sport facilities, in relation to the sport performed. In Europe, a unique standard regarding thermal comfort in sport facilities does not exist and the regulations may vary among the countries, as it happens in the USA. In particular, in Italy, the most important standard managing thermal comfort in sports halls is the guideline of CONI [73], which defines indications about air quality, thermal, lighting, and acoustic environment in sport halls and swimming pools. Table 4 shows the main values to be maintained in indoor sports halls and swimming pool, according to CONI's guidelines.

Table 4. Environmental parameters for sports halls and natatorium facilities (modified from [73])

	Air Temperature (°C)	Relative Humidity (%)	Ventilation Rate (Air Exchange/h) (2)	Maximum Air Velocity (m/s)	Environment
Indoor Sports Halls	16–20	50	(3)	0.15	Playing field
	20–22	50	(3)	0.15	Pre-athletic spaces
	18–22 (6)	50	5	0.15	Changing rooms
	22 (7)	70	8	0.15	Showers
	22	60	5–8	0.15	Sanitary facilities
	20	50	2.5	0.15	First aid
	20	50	1.5	0.15	Offices
	20	50	1	0.20	Halls
	16	50	0.5–1	0.25	Storage rooms
	20	50	0.5	0.20	Other spaces
Swimming Pools	(8) (5)	≤70 (8)	(8) (4)	≤0.10 (8)	Poolside
	28	70	3	0.15	Pre-athletic spaces
	≥20 (8)–24 (6)	60	≥4 (8)–5	0.15	Changing rooms
	24 (7)	70	8	0.15	Showers
	≥20 (9)	60	≥4 (8)–5–8	0.15	Sanitary facilities
	≥20 (8)–22	50	≥4 (8)	0.15	First aid
	20	50	1.5	0.15	Offices
	20	50	1.5	0.20	Halls
	20	50	0.5–1	0.25	Storage rooms
	20	50	0.5	0.20	Other spaces

Notes: (1) In the table are reported only the values concerning the thermal environment. The complete table can be found in [73]. (2) The values refer to the case of artificial ventilation. (3) At least 20 m^3/hour/person at maximum crowding for the spectator's area; 30 m^3/hour/person for the space occupied by the athletes. (4) Values to be established in relation to the thermo-hygrometric characteristics to be achieved. (5) For the water temperature in the pools, specific values are given by CONI's guidelines. (6) The temperature of the air in the changing rooms (excluding those of the swimming facilities) is appropriate to be 2–4 °C higher than that of the sport room. (7) The temperature of the water in the showers, must not be lower than 37 °C and not higher than 40–48 °C. (8) The thermo-hygrometric, ventilation and lighting engineering requirements must conform to what is indicated in the Agreement of 16 January 2003—between the Minister of Health, the Regions and the autonomous provinces of Trento and Bolzano on the sanitary aspects for the construction, maintenance, and supervision of the swimming pools.

However, since different sports present diverse requirements, International Federations often provide not only the rules regarding the game and the materials, but also standards concerning environmental parameters such as air temperature, relative humidity, and air velocity that should be maintained indoors for each sport. In Table 5 the environmental parameters provided for indoor sport facilities by federations recognized by the International Olympic Committee (IOC) are reported. It can be noticed that most federations show at least the values of air temperature that should be maintained in the playing area. However, several sport do not present any environmental value (e.g., boxing, fencing, etc.), therefore specific studies should be performed in order to define these parameters and to establish more precise values for the existing ones, since several sport federations report only the value of air temperature and they do not consider, for example, relative humidity, and air velocity.

Table 5. Environmental parameters to be maintained in the playing area given by sport federations.

Federation	Air temperature (°C)	Relative Humidity (%)	Maximum Air Velocity (m/s)
Aquatics (FINA) [74]	2 °C higher than water temperature (water temperature 25–28 °C)	-	-
Badminton (BWF) [75]	18–30	-	<0.2
Basketball (FIBA) [76]	16–20	<50	-
Boxing (AIBA)	-	-	-
Curling (WCF) [77]	6–7	controlled	No constant air movement
Fencing (FIE)	-	-	-
Gymnastics (IFG) [78]	Humidex = 22–38		-
Handball (IHF) [79]	15–22 (heated halls) 18–24 (cooled halls)	-	<1
Ice Hockey (IIHF) [80]	6	<70	-
Ice skating (ISU) [80]	6–12	<70	-
Judo (IJF) [81]	17–26	30–40	-
Table tennis (ITTF) [82]	12–25	-	<0.1
Taekwondo (WT)	-	-	-
Tennis (ITF) [83]	13–17 (winter) 6–8 below the external temperature (summer)	55–60	-
Volleyball (FIVB) [84]	>10 16–15 (for official competitions)	-	-
Weightlifting (IWF)	-	-	-
Wrestling (UWW) [85]	18–22	-	-

4. Thermal Comfort Models Applied to Sport Facilities

Sport facilities present high complexity, due to the different activities that are carried out in these environments. For this reason, experimental methods have been developed by researchers in order to predict or to assess the thermal conditions in swimming pools and sport halls. However, only a few studies has been developed, as shown by literature review displayed in Table 6.

Table 6. Literature review of the scientific papers regarding thermal comfort in sport facilities.

Reference	Investigation	Monitoring Duration	Environment
Stamou et al., 2008 [86]	Evaluation of the thermal comfort in the Galatsi Arena in Athens through a CFD analysis.	-	Indoor stadium
Rajagopalan and Luther, 2013 [16]	Thermal comfort prediction with the use of Fanger's indices, adaptive comfort models and questionnaires.	1 week	Sport hall within an aquatic center
Revel and Arnesano, 2014 [18]	Thermal comfort prediction with the use of Fanger's indices corrected for non-conditioned buildings in warm environments and questionnaires.	4 days	Swimming pool + Gym
Revel and Arnesano, 2014 [20]	Development of a monitoring technology that includes thermal comfort calculated with the use of Fanger's indices corrected for non-conditioned buildings in warm environments to obtain information on how energy is used in sport facilities.	4 days	Swimming pool + Gym

Table 6. *Cont.*

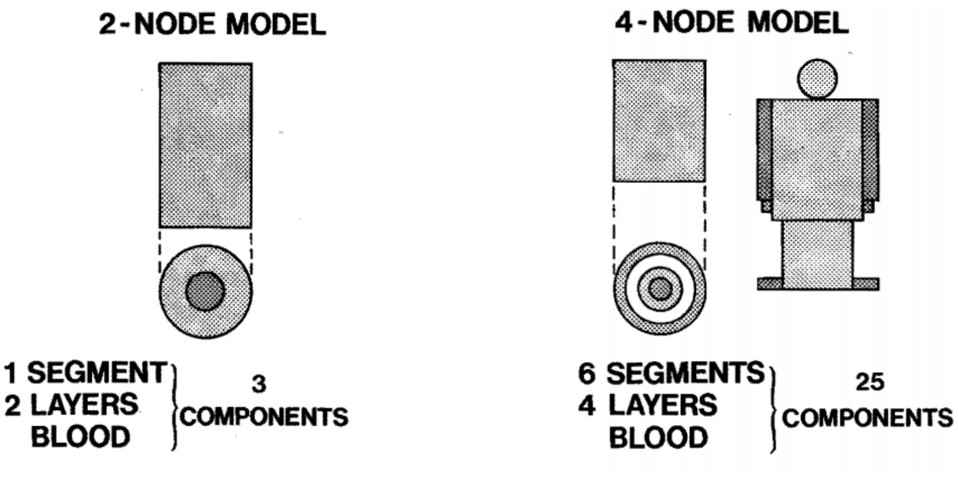
Reference	Investigation	Monitoring Duration	Environment
Kisilewics and Dudzinska, 2015 [14]	Measurements of the six basic parameters for the assessment of Fanger's indices. Calculation of the operative temperature.	2 days	University sports hall
Zhai et al., 2015 [21]	Thermal comfort assessment with the use of questionnaires and its relation to air movement. Estimation through questionnaires of thermal responses, perceived air quality and Rate of Perceived Exertion (RPE).	-	Climate chamber
Cheng et al., 2016 [87]	Parametric modeling to predict and control thermal comfort and ventilation, based on the adaptive approach.	-	University multisport facility
Cianfanelli et al., 2016 [19]	Thermal comfort prediction with the use of Fanger's indices and questionnaires.	2 months	Swimming pool + Polyvalent sport center
Khalil and Al Hababi, 2016 [88]	Investigation of thermal comfort in a gymnastic hall with the use of CFD for the calculation of PMV under different conditions.	-	Gymnastic sports hall
Lebon et al., 2017 [15]	Numerical analysis for the assessment of thermal comfort in an indoor swimming pool, through the calculation of Fanger's indices and Humidex index.	-	Swimming pool
Zora et al., 2017 [22]	Investigation on the relation between Fanger's index Predicted Mean Vote (PMV) and Rate of Perceived Exertion (RPE). Detection of skin and core temperatures.	-	Climate chamber
Bugaj and Kosinski, 2018 [17]	Thermal comfort prediction with the use of Fanger's indices and evaluation of possible improvements to improve the conditions of comfort.	3 days	Indoor tennis court
Berquist et al., 2019 [89]	Assessment of thermal comfort using questionnaires	5 months (12 h per day)	Gymnastic center

4.1. *Human Thermal Physiological Models*

In order to determine the thermal comfort, several physiological models have been developed, from the one-node model, representing the complete human body as one node [90] to the more complex and realistic ones, representing the body with a multi-elements model using finite elements [91]. In sport applications, the most used models are [92]:

- Gagge's model, used for quasi-stationary conditions;
- Stolwijk's model, used for non-stationary situations;

The model of Gagge consists of a two-nodes model of the human body, representing the core and the shell, while the model of Stolwijk is a four-node model representing trunk, arms, hands, legs, and feet (Figure 6).



(**a**) (**b**)

Figure 6. Human thermal physiological models: (**a**) Gagge's model; (**b**) Stolwijk's model [92].

The model of Gagge is used for most of the activities, while the model of Stolwijk is generally used only for the description of a wet swimmer coming out from the water. These models define the relation between individual parameters such as the metabolic rate and the clothing insulation with the environmental parameters, usually described by air temperature, relative humidity, mean radiant temperature, and air velocity.

For swimmers, thermal comfort depends on the time, due to the heat loss occurring because of the evaporation of the water on the skin, as swimmers are subjected to a drying process, which can be divided in two intervals [92].

- Interval 1: starting as soon as the swimmer leaves the pool and ending 10 min later;
- Interval 2: when the body is dry (it is a steady-state condition);

In particular, the adaptation of the model of Stolwijk to the wet swimmer (during interval I) includes the addition of an evaporative term [92]

$$E(I) = (p_{skin}(I) - p_a)\ 2.2\ h_c(I)\ (10\ v_a)^{1/2}\ f_{pcl}(I)\ S(I) \tag{14}$$

where E(I) is the evaporative heat loss of segment I of a wet body (W), p_{skin} is the saturated water vapor pressure at the skin of segment I (Pa), p_a is the water vapor partial pressure of the air (Pa), h_c is the convective heat transfer coefficient (W/m^{2}K), v_a is the air velocity (m/s), f_{pcl}(I) is the Nishi's permeation efficiency factor of segment I and S(I) (m^2) is the surface area of segment I.

For the calculation, usually the segment I is assumed equal to the nude part of the swimmer's body. The drying process is a transient condition, therefore the evaporative heat loss starts from an initial amount and ends when E(I) = 0 and the skin surface is dry. If the condition is when the drying process is just started (swimmer gets out of the pool), the p_{skin} can be calculated for a temperature equal to the pool temperature [18]. For the dry swimmer (Interval II) the evaporative term should not be considered [92].

4.2. Predictive Indices used to Assess Thermal Comfort

In moderate climates, the thermal environment is defined through six basic parameters: four environmental (air temperature t_a (°C), relative humidity RH (%), mean radiant temperature t_r (°C), and air velocity v_a (m/s)) and two individual (clothing insulation I_{cl} (clo) and metabolic rate M (Met)). It is the interaction of these factors which determines the thermal sensation of humans [23]. However, considering sport facilities, the conditions cannot be considered 'standard', as the metabolic activity can be very high and clothing insulation may vary according to the sport apparel worn and to the increased air velocity due to the body movement. For this reason, in these environments the correct estimation of the individual parameters has a fundamental role in the prediction of the thermal sensation of the athletes.

4.2.1. Fanger's Indices PMV and PPD

Most of the studies were based on the calculation of Fanger's indices, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD), derived from field measurements [14,16,17,19,22] or from simulations obtained through computational fluid dynamics (CFD) models [86,88].

PMV index is defined as the vote of an average individual regarding the thermal environment and it is a function of the six basic parameters, shown in Table 7. The calculation of this index requires an iterative method; therefore, it is generally performed through software, or directly by data loggers. The purpose of Fanger's indices is to correlate environmental and individual parameters to the subjective feeling of humans. Thus, Fanger proposed an experiment on 1296 individuals who, after remaining in a thermal chamber, had to give an answer regarding the thermal environment on a seven-point sensation scale, defined by ASHRAE (from -3 cold to +3 hot). Based on this survey, Fanger proposed the equation [93]

$$\mathrm{PMV} = (0.303\ \mathrm{e}^{-0.036\mathrm{M}} + 0.028)\ \mathrm{S} \tag{15}$$

where M is the metabolic rate and S is the heat storage.

Table 7. Environmental and individual parameters used for the definition of PMV and PPD.

Parameter		Symbol	Unit
Environmental Parameters	Air Temperature	t_a	°C or K
	Mean radiant temperature	t_r	°C or K
	Partial pressure of water vapor	p_a	Pa
	Air velocity	v_a	m/s
Individual Parameters	Metabolic rate	M	W/m^2 or Met (1 Met = 58.2 W/m^2)
	Thermal insulation of clothing	I_{cl}	m^2 K/W or Clo (1 Clo = 0.55 m^2 K/W)

PPD index is defined as the predicted percentage of dissatisfied with regard to a certain environment, considering dissatisfied a person who, subjected to a certain thermal environment, express a rating of +3, +2, −2, or −3 on the thermal sensation scale. The relation between the PMV and PPD is [93]

$$\mathrm{PPD} = 100 - 95\ \mathrm{e}^{0.03353\ \mathrm{PMV}\hat{}4\ +\ 0.2179\ \mathrm{PMV}\hat{}2} \tag{16}$$

Note that the condition in which every subject is satisfied does not exist, and the minimum value of PPD is 5%.

However, the PMV method presents some limits, as indicated in the UNI EN ISO 7730 [70]. In fact, this method is applicable only when the environment can be defined moderate (PMV is less than 2 in absolute value) and when the six basic parameters stay within the limits shown in Table 8. This leads to the consideration that this method can present several problematics in the application to sport facilities, as the metabolic rate often exceeds the value of 4 Met.

Table 8. Range of applicability of environmental and individual parameters for the calculation of PMV [70].

Parameter		Range	Unit
Environmental Parameters	t_a	+10–+30	°C or K
	t_r	+10–+40	°C or K
	p_a	0–2700	Pa
	v_a	0–1	m/s
Individual Parameters	M	0.8–4	W/m^2 or Met (1 Met = 58.2 W/m^2)
	I_{cl}	0–2	m^2 K/W or Clo (1 Clo = 0.55 m^2 K/W)

4.2.2. Fanger's Indices PMV Corrected for Warm and Humid Environments (ePMV)

In some other cases [18,20] the PMV index was calculated considering the correction for non-air-conditioned buildings in warm climates, provided by Fanger and Toftum [94].

This model introduces the expectancy factor (e) shown in Table 9 that should be multiplied for the PMV in order to obtain the real thermal sensation of the athletes. This index is used to describe the perception of non-conditioned-buildings' occupants, as they may feel sensations of warmth less severe than the one predicted by PMV, due to their low expectations and factors related to metabolic activity [94].

Table 9. Expectation factor (e) for non-air-conditioned buildings in warm climates [18].

Expectation	Classification of the Building	Expectation Factor e
High	Non-ventilated buildings located in regions where air-conditioned buildings are common. Warm period occurring briefly during the summer season.	0.9–1.0
Moderate	Non-ventilated buildings located in regions with some air-conditioned buildings. Warm summer season.	0.7–0.9
Low	Non-ventilated buildings located in regions with few air-conditioned buildings.	0.5–0.7

In particular, the ePMV can be calculated as

$$\text{ePMV} = \text{e PMV} \tag{17}$$

In the research of Revel and Arnesano [18,20], the expectancy factor was considered equal to 0.7. Furthermore, for the evaluation of the PMV in the swimming pool, the condition of the swimmer just coming out from water was considered and the evaporative term described by [14] has been added for the calculation of the PMV.

4.2.3. Adaptive Comfort Model

The adaptive thermal comfort model has been applied for the parametric modeling used to predict and control of thermal comfort in a university multisport facility [87] and for spectators of a sport hall within an aquatic center [16], on the basis of the model of de Dear and Brager. In this model, it is taken into consideration that in general people in warm climate zones prefer warmer indoor temperatures than others living in cold climates [95]. This study consists of a statistical analysis which showed that occupants in naturally ventilated buildings present a wider tolerance with regard to the range of temperatures that can be recorded indoors.

4.2.4. Operative Temperature

The operative temperature has been calculated for the assessment of the thermal environment in an indoor sport hall during summer period [14]. The operative temperature is often used for the assessment of the thermal environment, even if it is not considered in the six basic parameters and it depends on radiative and convective exchanges. It can be calculated as [55]

$$t_o = \frac{h_r \cdot t_r + h_c \cdot t_a}{h_r + h_c} \tag{18}$$

where:

h_c = unitary convective conductance (W/m^2 K)
h_r = unitary radiative conductance (W/m^2 K)
t_a = air temperature (°C)
t_r = mean radiant temperature (°C)

Since there are some difficulties in evaluating the operative temperature with this equation, two simplified expressions for its calculation exist. The first provides a value of the operative temperature dependent on the relative air velocity by means of a coefficient A,

$$t_o = A\ t_a + (1 - A)\ t_r \tag{19}$$

where A = 0.5 when the relative air velocity is lower than 0.2 m/s, A = 0.6 when the relative air velocity is between 0.2 and 0.6 m/s, and A = 0.7 when the relative air velocity is between 0.6 and 1.0 m/s.

The second expression is an arithmetic mean of values of the two temperatures from which the operative temperature depends

$$t_o = (t_a + t_r)/2 \tag{20}$$

4.2.5. Humidex

The humidity index (humidex) has been used to assess thermal comfort in a swimming pool [15]. This index is a dimensionless number which allows the evaluation of air temperature and humidity on an average person. It has been proposed for the evaluation of environments which presented high humidity as an alternative to the Fanger's indices. The value of humidex is given by [93]

$$\text{Humidex} = t_a + [5.555\ (\text{Pa} - 1.013)] \tag{21}$$

where:

t_a = air temperature (°C)
pa = partial vapor pressure (kPa)

Humidex identifies 4 different thermal levels, from the comfort level (level 0) to the definition of possible health risks (level 4).

4.3. Subjective Judgements Used to Assess Thermal Comfort

Even if this aspect is often underestimated, the perception of a thermal environment is strongly related to the psychological conditions. For this reason, most of the researchers in their studies assessed the thermal sensation of the athletes with the use of questionnaires [18,19,21,89]. In particular, with regard to the subjective perception of the thermal environment, the research of Revel and Arnesano [18] compared the predictive models to the subjective responses in order to determine the impact of high metabolic rates and sport garments on systematic errors in the prediction of Fanger's indices.

For the design of the questionnaires, UNI EN ISO 10551 Standard [96] regulates the subjective evaluation of the thermal environment, which consists of judgement scales regarding perception, comfort, and thermal preference and, in some cases, personal acceptability and tolerance. In particular, the scale of perception in moderate environments is represented on a seven-point scale showing the thermal sensation vote (TSV), which can be compared to the PMV. Furthermore, the evaluative scale shows the feeling of comfort of the subjects on a unipolar scale from 0 to 4, in which points 3 and 4 are characterized by an increasing level of discomfort and can be considered dissatisfied. For this reason, this scale can be compared to Fanger's PPD.

4.4. Thermal Environment and Performance: Correlation between PMV and RPE

The perception of the thermal environment has a great influence on the performance, which is related directly to the kind of activity that has to be carried out in terms of concentration, physiological effort, etc. Several studies have been performed on the problems related to the heat stress of the athletes in hot and humid environments, but little knowledge is available in moderate environments. In fact, even if in these environments the safety of the athletes is not usually compromised, their performance may be affected by certain ambient parameters. For this reason, in sport facilities, the impact of the thermal environment on the athletes has been considered, as better conditions could improve the efficiency of a training session, or even the performance in a competition. In particular, studies were carried out in order to correlate the Fanger's index PMV to the rate of perceived exertion (RPE), in order to find an association between the thermal and the physiological responses of athletes during exercise [22]. Furthermore, Zhai et al. [21] studied the effect of air movement for comfort during exercise at different levels of metabolic rate and the relation between the thermal sensation and the perceived exertion. In these researches, physiological characteristics such as the oxygen consumption, skin, and core temperatures were also detected. It resulted that PMV is related to RPE, thus increasing the condition of thermal comfort in sport facilities may have positive results also on the performance of the athletes.

5. Thermal Comfort Assessment in Practice

The assessment of thermal comfort in sport facilities presents some difficulties due to the complexity of these environments. In fact, often sport halls are multifunctional buildings, used for the practice of several sports. Furthermore, in sport facilities the activities carried out are not stationary, thus the six basic parameters cannot be assessed as in other environments such as offices, school buildings, etc. In this section, a review of the methodologies used to assess thermal comfort in sport facilities is reported.

5.1. Monitoring Duration

The monitoring duration was 2 days at minimum and 5 months at maximum. Data were recorded with a minimum of 15 seconds to a maximum of 15 min. The time of acquisitions varies largely in relation to the kind of environment investigated. When the conditions change rapidly, the acquisition time must be shorter (every 15 sec–1 min), otherwise data can be recorded every 15 min. Any standardized procedure was revealed by the review of the existing research on thermal comfort in sport facilities and the measurements were carried out in relation to the problematics of the case of study.

5.2. Assessment of the Individual Parameters

5.2.1. Metabolic Rate

The metabolic rate can be determined by UNI EN ISO 8996 standard [53], which contains the data to calculate it with tables provided for different activity levels. However, more accurate estimation can be provided by studies concerning the level of metabolic activity of the sport considered [54]. For varying metabolic rates, standard UNI EN ISO 7730, suggests a time-weighted average that should be estimated during the previous 1 h of activity [70].

In the research of Revel and Arnesano [18], three phases were examined: transitory phase, steady state, and recovery state. These phases should be considered in the calculation of PMV, as they imply exercise levels. In fact, also the intensity of the exercise is fundamental for the metabolic production. In particular, sedentary activities are characterized by values around 1.0–1.5 Met, light intensity 1.6–2.9 Met, moderate intensity 3–5.9 Met, and vigorous intensity > 6 Met [54]. The correct evaluation of the metabolic rate is fundamental for the calculation of PMV and PPD, as mistakes in the assessment may lead to uncertainties. For this reason, researchers should focus on the determination of this parameter, in order to perform a correct evaluation of the thermal sensations.

5.2.2. Clothing Insulation

Standard UNI EN ISO 9920 [27] provides a procedure for the evaluation of the clothing insulation with tables reporting I_{cl} values (m^2 K/W) for several clothing types. However, often sport garments are not included in this standard, thus specific research on the values of their insulation have been used by researchers, in order to provide a more precise estimation.

In sport facilities the clothing worn can be the same for all the athletes (in case in which a particular uniform is worn) or, more commonly, the garments may change according to the personal preference. For this reason, researchers calculated values of PMV and PPD for different clothing ensembles [17] or they were asking in questionnaires provided to users which were the garments worn during sport activity at the time of the test [18]. In the cases in which the movement of the human body was relevant and it modified the thermal insulation of the clothing due to the pumping effect, the correction proposed by UNI EN ISO 9920 was considered [27]. This correction is a function of air velocity and metabolic rate and it involves a decrease of the thermal insulation of the garments, which allows a greater heat transfer.

5.3. Measurement of the Environmental Parameters

The measurement of the four environmental parameters is also fundamental for the determination of the Fanger's indices. In buildings such as offices, where stationary activities are carried out, the probes are usually located close to the workstation or, in any case, in the proximity of the locations occupied by building users [55]. In sport facilities, athletes do not occupy a fixed position, thus the procedure for performing the measurements is more complex. However, in the review of the existing research, it resulted that the location of the probes in the sport facilities was standardized, as they were situated at a height varying from 0.6 m for the sitting position to 1.1–1.7 m for the standing position, usually in the center of the hall or, in the case of the swimming pool, close to the water [20].

6. Conclusions

In sport facilities, ensuring thermal comfort is particularly relevant, as it may affect the performance and health of the athletes. Thermal environments can be seen as a combination of physical, physiological, and psychological factors, and the interaction between these three aspects determines the thermal sensation of humans. In particular, in spaces in which physical activity is carried out, the physiological component is particularly relevant, as the metabolic rate is high and therefore the body produces a consistent amount of heat, which must be dispersed in the environment.

In order to predict the thermal sensation of the athletes performing in indoor sport facilities, most researchers focused on the calculation of Fanger's indices PMV and PPD. However, even if a correlation between the PMV corrected for warm and humid environments and the real sensation determined through questionnaires was found, the high metabolic rate occurring during sport practice may lead to an overestimation of the thermal sensation of the athletes. Furthermore, since sport facilities are multifunctional buildings in which several activities are carried out, the difficulties that have to be faced also concern the determination of a thermal environment which is comfortable for all the occupants, from the athletes to the spectators.

From the literature review, it results that only little knowledge is available on the determination of thermal comfort in indoor sport facilities and on the standardization of a measurement protocol to be applied in these spaces. Moreover, there is a lack in standards concerning the environmental parameters that should be maintained in sport halls. For this reason, further research should be developed on this topic, as performing in a comfortable environment may improve the performance of athletes and ensure healthy and pleasant conditions.

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