Applicability of existing models for predicting thermal comfort in sports facilities through the analysis of a case study

**Giulia Lamberti[1,2*], Fabio Fantozzi[2], Francesco Leccese[2],
Giacomo Salvadori[2]**

1: University of Pisa, Pisa, Italy;
2: Institut de Recherche en Constructibilité, Université Paris-Est, France

giulia.lamberti@phd.unipi.it

1. Abstract

Ensuring thermal comfort within sports facilities is crucial for occupants' well-being. However, often indices designed for sedentary spaces are applied, leading to inaccurate comfort assessments. Hence, this study examines the adaptive capacities and model applicability in sports facilities, using a fencing hall located in Pisa as a case study.

Data encompassed 142 subjective responses correlated with environmental parameters. Athletes' neutral and preferred temperatures were notably lower than sedentary individuals' (15.1°C and 16.8°C, respectively). Fanger's PMV tended to overestimate thermal sensation at high metabolic rates, and occupants felt more varied sensations than predicted, displaying greater acceptance of warmth than cold. Athletes' adaptive capacities differ from sedentary occupants', with neutral temperatures frequently below comfort standards. This study underscores the necessity of analysing athletes' comfort and exploring adaptation possibilities due to distinct needs and preferences compared to sedentary occupants.

Keywords - Adaptive thermal comfort, Offices, North-East India, Probit analysis, Preferred temperature.

2. Introduction

In the past decade, enhancing indoor comfort in terms of air quality, thermal, visual, and acoustic aspects has grown increasingly important (Bluyssen, 2019). While researchers have investigated spaces like offices (Lou & Ou, 2019), schools (Torriani et al., 2023), and dwellings (Peeters et al., 2009), few studies exist for sports facilities (Fantozzi & Lamberti, 2019). Indeed, sports halls are multipurpose structures hosting various activities, which pose a challenging comfort issue that researchers must address, given the rising significance of sports in daily life. Studies on indoor environmental quality in sports facilities have increased, focusing notably on air quality and thermal comfort (Andrade et al., 2017). Indoor air quality significantly impacts athletes' health, with exercise environments influencing practitioners' well-being, and the thermal environment's assessment, particularly concerning energy consumption, has also gained attention (Braniš et al., 2009).

This research has focused on swimming pools (Cianfanelli et al., 2016; Rajagopalan & Luther, 2013; Revel & Arnesano, 2014b), gyms (Berquist et al., 2019; Khalil & Al-hababi, 2016; Revel & Arnesano, 2014a), and climate chambers (Zhai et al., 2015; Zora et al., 2017), and indices such as operative temperature (Kisilewicz & Dudzińska, 2015) and humidex (Lebon et al., 2017) have been examined. Objective-subjective comparisons via questionnaires to assess occupants' responses were also carried out (Berquist et al., 2019; Cianfanelli et al., 2016), as the perception of the thermal environment correlates may vary among different individuals. Recent studies have employed Infrared Thermography to examine athletes' thermal behaviour (Lamberti et al., 2020), enhancing thermal state evaluation.

Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are commonly used indices to assess thermal comfort (Kisilewicz & Dudzińska, 2015; Rajagopalan & Luther, 2013), even with warm-humid correction ePMV (Revel & Arnesano, 2014b) and its relation to Rate of Perceived Exertion (RPE) (Zora et al., 2017).

Yet, the suitability of these models for sports facilities remains unexplored. PMV and PPD, developed in climate chambers, lack occupant adaptability consideration (Singh et al., 2011), which is crucial for athletes. Real-world comfort involves wider conditions than the models acknowledge, impacting energy consumption and HVAC usage (Yang et al., 2014), and inappropriately applied models may increase energy use and reduce comfort.

Given high energy usage in sports facilities, examining existing models is therefore needed. Thus, this paper aims to evaluate the adaptive capacities of athletes and the applicability of current thermal comfort models in this building type.

3. Methods

3.1 The case study

The evaluation of thermal comfort was carried out in the fencing hall "Club Scherma Pisa Antonio di Ciolo" located in Pisa, Italy, which is a pillar of national and international fencing.

The fencing hall is characterised by a rectangular area of about 390 m^2, with a ridge height of 5.90 m. It is a tensile structure with laminated wood beams and steel columns, covered with a white double membrane of PVC polyester fabric. The 12 fencing pistes occupy a space of approximately 228 m^2. The fencing hall is naturally ventilated, with a heating system constituted by a generator of warm air, located at about 3 m of height on the north side.

3.2 Monitoring campaign

The measurement campaign was carried out during spring 2019, from 17:00 to 21:00, when the athletes were training. The activities in the sports hall can be divided into four parts, as shown in Table 1. The air (Ta), globe temperatures (Tg), relative humidity (RH), air velocity (Va), and CO2 concentration were measured with a microclimate data logger in compliance with ISO 7726 (ISO7726, 2001). Outdoor temperature (Tout) and relative humidity (RHout) were also measured. Probes were located in representative locations of the hall, at a height of 1.1 m to evaluate the standing position of the fencers. Then the clothing insulation (Icl) was evaluated from ISO 9920 (ISO 9920, 2001) and considering the specific characteristics of the fencing uniforms (Leon Paul, 2016), taking into account the pumping effect. Values of clothing insulation are reported in Table 1.

Table 1: Activities carried out during the training and the corresponding clothing insulation and metabolic rate.

	Time	**Activity**	**Clothing ensemble**	**I_{cl} (clo)**	**M (met)**
Part 1	17:00 – 18:00	Warm up – Physical exercises	Underwear, T-shirt, Sport trousers	0.45	3.8
Part 2	18:00 – 19:00	Fencing	Fencing uniform	0.82	2.7
		Warm up – Physical exercises	Underwear, T-shirt, Sport trousers	0.45	2.7
		Warm up – Fencing	Fencing uniform	0.82	2.4
Part 3	19:00 – 20:00	Fencing	Fencing uniform	0.82	2.8
Part 4	20:00 – 21:00	Fencing	Fencing uniform	0.82	2.8

The metabolic rate was determined by considering ISO 8996 (ISO 8996, 2005) and the values provided for different sports provided by the Compendium of Physical Activity (CPA) (Ainsworth et al., 2011). In this study, the method developed by Fletcher et al. (Fletcher et al., 2020) for the calculation of metabolic rate in sports facilities was applied. This method states that "for varying metabolic rates, a time-weighted average should be estimated during the previous 1-h period", thus the following equation was used:

$$M = \frac{1}{T}\sum_{i=1}^{n} M_i \cdot t_i \qquad (1)$$

Where M is the time-weighted metabolic rate for the work cycle (Met), T is the total duration of the work cycle (min), Mi is the metabolic rate of activity in the work cycle (Met) and ti is the duration of the activity in the work cycle (min). Each activity was observed during the study and then the M was used to calculate PMV.

For the input parameters, the international standard for PMV calculation prescribes an upper limit of 4 Met. Many sports activities present higher values, but for the case study, the metabolic rate for the complete work cycle never exceeded this threshold value.

3.3 Subjective measurements

During the monitoring campaign, questionnaires in compliance with ISO 10551 (ISO 10551, 2019) were submitted to the athletes after at least one hour of exposure. Questionnaires were submitted in Italian, as it is the language spoken by athletes in the fencing hall. The following questions were asked:

1. General information (age, gender, date, time);
2. Thermal Sensation Vote (TSV) on ASHRAE's 7-points scale;
3. Thermal Comfort Vote (TCV), expressed as a vote from 1 (comfort) to 4 (much discomfort);
4. Thermal Preference Vote (TPV), expressed as a vote on a 7-points scale.

The validation of the questionnaires was ensured with the observation of the congruence between the answers.

3.4 Data analysis

The mean radiant (Tr) and operative (Top) temperatures were calculated according to the ISO 7726 standard (ISO 7726, 2001).

Then, the running mean outdoor temperature (Trm) was calculated in compliance with the EN 16798-1 standard (EN 16798-1, 2019).

Fanger's PMV and PPD indices were calculated in line with the ISO 7730 standard (ISO 7730, 2006). Subsequently, the objective and subjective measurements were analysed to establish a link between the environment's perception and students' exposure, and each athlete's response was associated with the environmental parameters to which they were subjected at the time and in the position under consideration. In total, 142 samples of subjective responses associated with environmental parameters were collected.

4. Results and discussion

4.1 Evaluation of the environmental parameters

Table 2 presents a statistical overview of the parameters recorded from the measurement campaign. Indoor temperatures consistently remained below 20°C, indicative of the relatively cool environment. Relative humidity predominantly remained within comfort parameters, averaging 61.9%. Air velocity registered a consistently low average of 0.02 m/s. Metabolic activity varied between 2.4 and 3.8 met, while clothing insulation averaged 0.82 clo, representative of the fencing uniform's thermal insulation.

Air quality maintained a healthy condition, with CO2 concentration averaging below 1410 ppm. Notably, this level remained acceptable despite athletes' heightened activity, potentially due to the naturally ventilating characteristics of the tensile structure.

The structure's high permeability aligns indoor conditions (Tout and RHout) closely with outdoor conditions, albeit with higher indoor temperatures and relative humidity.

Table 2: Statistical overview of the monitored parameters in the fencing hall.

	T_a	RH	V_a	T_r	T_{op}	M	I_{cl}	T_{out}	RH_{out}	CO_2
Mean	15.9	61.9	0.02	15.8	15.9	2.8	0.82	11.3	48.1	1410
SD	1.8	11.7	0.01	1.8	1.8	0.2	0.10	1.4	18.5	240
Maximum	19.1	81.3	0.11	19.1	19.1	3.8	0.45	13.3	80.8	1808
Minimum	12.2	38	0.00	12	12.1	2.4	0.82	8.2	29.5	862

4.2 Definition of neutral and preferred temperatures

To evaluate athletes' thermal comfort, the neutral (TN) and preferred (TP) temperatures were calculated. TN corresponds to the operative temperature where thermal sensation is neutral (TSV=0), and TP indicates the temperature at which occupants express no change in the thermal environment (TPV=0).

TN and TP were calculated through the weighted linear regression between Top and TSV and TPV, as shown in Figure 1, binning data considering 0.5°C steps. The regressions, shown in Figure 1, were statistically significant (p-value<0.05).

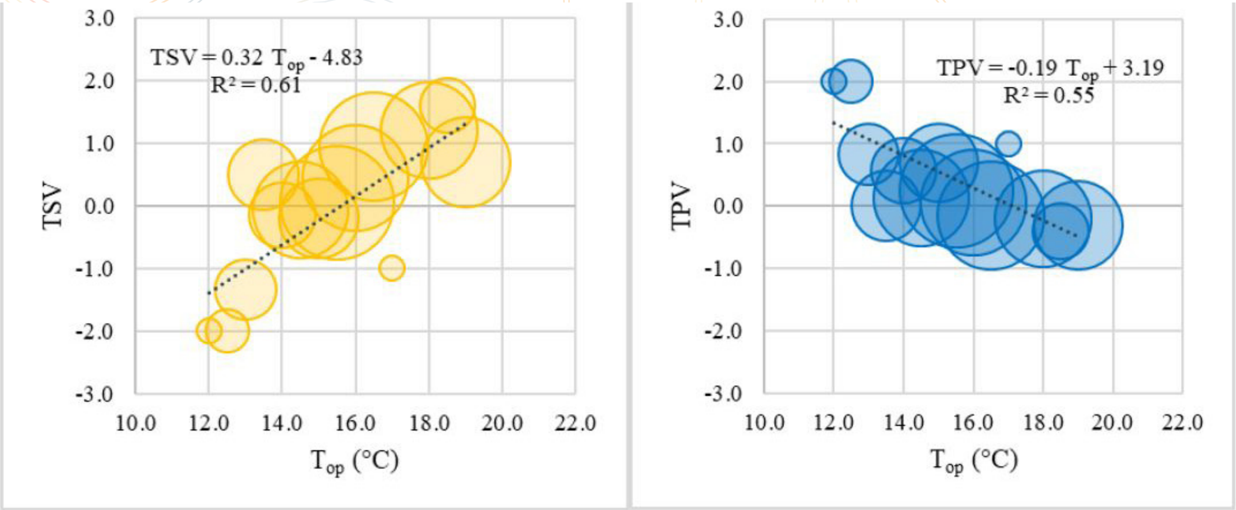

Figure 1: Relationship between Top, TSV, and TPV in the fencing hall.

Examining the correlation between Top and TSV reveals a notable sensitivity of athletes' thermal sensation to operative temperature, as evidenced by the steep slope. Instead, the relation between Top and TPV shows a shallower slope, which highlights that changes in thermal preference are less dependent on operative temperature. Regression analysis yielded TN and TP values of 15.1°C and 16.8°C, respectively, for athletes. Remarkably, TP is higher than TN, implying athletes perceive thermal neutrality at lower temperatures while favouring warmer conditions.

These relatively low TN and TP may be attributed to two factors. Firstly, heightened metabolic rates significantly lower comfort temperatures. Secondly, athletes exhibit robust adaptive capacities during winter, even under challenging indoor climate conditions.

4.3 Applicability of Fanger's PMV to sports facilities

The applicability of the Fanger model to sports facilities was analysed using three methods (Cheung et al., 2019): (i) the analysis of the Bias, Mean Absolute Error (MAE), and Root Mean Square Deviation (RMSD) error indices; (ii) the analysis of the relationship between PMV and TSV; and (iii) the comparison between thermal sensation and the percentage of dissatisfied.

4.3.1 Analysis of error indices

To assess the predictive ability of Fangers' method, the MAE, RMSD, and Bias between the calculated PMV and individual TSV were determined.

The MAE was 1.13, which shows that the PMV is, on average, more than one scale unit different than the real thermal sensation in sports facilities. This result is consistent with the findings reported by Humphreys and Nicol (MAE=1.00) (Humphreys & Nicol, 2002), Doherty and Arens (MAE=1.26) (Doherty & Arens, 1988), and Cheung et al. (MAE=1.02) (Cheung et al., 2019) for everyday environments. The RMSD, which shows the average difference between the predicted and the measured thermal sensation, was compared to the standard deviation of TSV (Koelblen et al., 2018). RMSD was 1.34 and remained below the Standard Deviation of TSV (SD=1.41).

The Bias between the PMV and the TSV was 0.04, which remains in the acceptable range of ±0.25 given by Humphreys and Nicol (Humphreys & Nicol, 2002). Nevertheless, there is to notice that the use of the Bias only as an indicator may lead to misinterpretation of the data because positive and negative errors cancel out.

4.3.2 Relationship between PMV and TSV

To account for the fact that PMV predicts the thermal sensation of a group of individuals subjected to specific environmental conditions, the data were clustered according to the environmental parameters. To this aim, a weighted regression analysis was carried out, considering 0.5°C increments in the indoor operative temperature (Torriani et al., 2023).

Figure 2 shows the relationship between TSV and PMV, revealing a consistent correlation (R2=0.67). PMV=0 (neutral sensation) yields a TSV below zero (cold sensation), again highlighting PMV overestimation of the thermal sensation for high metabolic rates. Moreover, PMV predictions remain restricted in range compared to recorded TSV values, emphasizing the discrepancy, especially on the cold side of the ASHRAE scale.

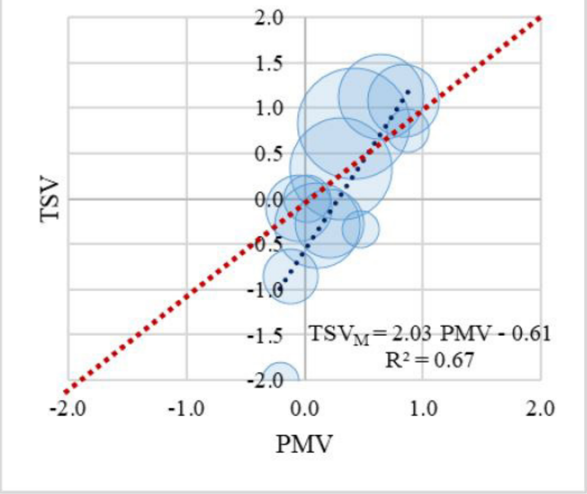

Figure 2: Relation between PMV and TSV. The blue line shows the recorded relationship between PMV and TSV, while the red line the ideal one. The dimensions of the circles show the dimension of the clusters.

4.3.3 Relationship between thermal sensation and the percentage of dissatisfied

This section examines the relationship between TSV and the Percentage of Dissatisfied (PD) and Fanger's PMVPPD curve. For PD calculation, those voting +3 (discomfort) or +4 (much discomfort) on the TCV were considered dissatisfied.

Figure 3 shows the TSV-PD relationship (blue) against the PMV-PPD curve (red). Unlike the PMV-PPD curve, the observed TSV-PD relationship is asymmetrical. The Percentages of Dissatisfied are significantly higher in cold environments (98% vs. 31% in warm conditions). Athletes tended to accept warmer sensations, probably due to their association with exercise. This aligns with the curve's minimum shifting toward positive values (around +1), reflecting athletes' preference for warmth. Moreover, the curve reaches a minimum dissatisfaction percentage of 0%, diverging from the PMV-PPD curve with a 5% minimum.

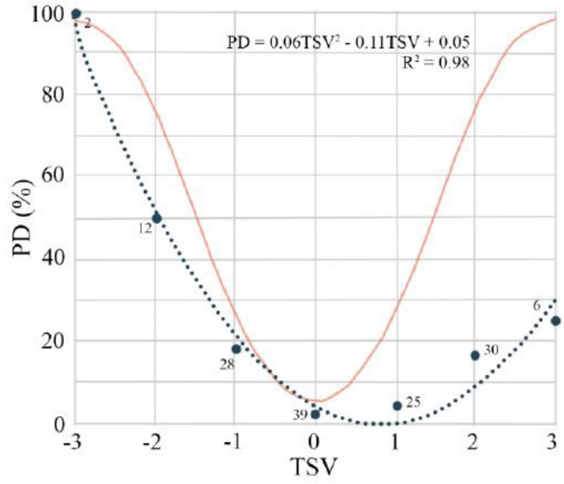

Figure 3: Relationship between the thermal sensation and the percentage of dissatisfied. In blue, the relationship between TSV and PD, while in red the Fanger's relationship between PMV and PPD. The numbers on the points show the dimension of the clusters.

4.4 Investigating adaptation in sports facilities

Neutral temperatures were then analysed in relation to the adaptive relationship. Since adaptation can also take place under winter conditions (Lamberti et al., 2023), the cases in which Trm was below 10°C were taken into account, considering constant comfort areas (Nicol et al., 2012), as shown in Figure 4.

To derive the athletes' neutral temperatures, the Griffiths method was used, considering a sensitivity coefficient (Griffiths' constant) of 0.5°C-1, in compliance with the SCATs project (Nicol et al., 2012). This value was chosen because there are currently no studies defining the thermal sensitivity of athletes during sports and thus can give a first indication of the values that the neutral temperatures can assume.

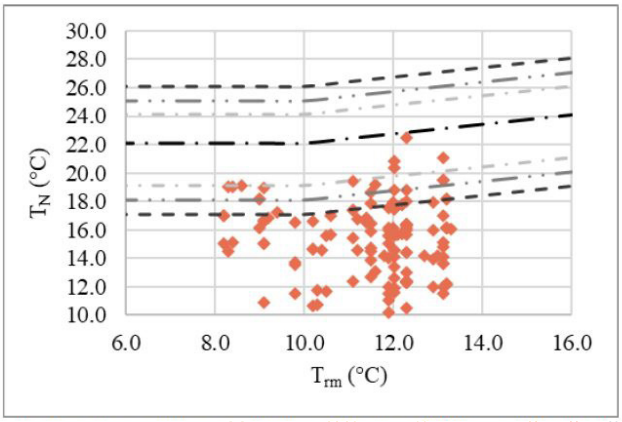

Figure 4: Neutral temperatures and their relationship with the adaptive relationship.

Displayed in Figure 4 is the adaptive connection alongside user-determined TN assessed via Griffiths' method. Notably, Griffiths' calculated neutral temperatures often fall remarkably low, considerably beneath the comfort thresholds specified by standards for sedentary environments.

These outcomes underscore the starkly contrasting thermal comfort requirements for athletes. Even implementing an adaptive model may not necessarily ensure their comfort. Given the potential impact of accurate thermal sensation assessment on comfort and energy usage, a comprehensive examination of comfort within sports facilities becomes imperative, including the prospect of developing tailored adaptive models for such structures.

4.5 Limitations

While highlighting athletes' thermal perception, this study presents some limitations necessitating consideration. Notably, the dataset comprises a modest 142 responses. Although comparable sample sizes have informed previous studies, a more extensive survey pool would be needed for deriving adaptive models pertinent to athletes. Then, the calculation of neutral temperatures via Griffiths' method employed thermal sensitivities from the SCATs project, which doesn't encompass sports settings. While offering valuable insights into athletes' TN, their distinct thermal sensitivity might vary. Furthermore, the application of Griffiths' method occasionally yields notably low neutral temperatures, as documented in earlier studies across different settings. (Rupp et al., 2019).

5. Conclusion

This study analyses comfort within sports facilities, focusing on the experiences of international fencing athletes during their training sessions. A comprehensive analysis was conducted, gathering a total of 142 subjective responses that were linked to measured environmental parameters.

The findings highlighted that athletes' neutral and preferred temperatures diverge from those of sedentary individuals (TN=15.1°C, TP=16.8°C). This disparity can be attributed to the heightened levels of metabolic activity exhibited by athletes during their training.

An examination of Fanger's model highlights that the Predicted Mean Vote (PMV) tends to overestimate the thermal sensations experienced by athletes, particularly when their metabolic rates are high. Moreover, the responses from the fencers indicate a broader spectrum of sensations than what the model projected.

The relationship between thermal sensation and dissatisfaction rate, as observed in sports facilities, displays an asymmetry. Notably, there exists a minimum threshold for warmth sensation (TSV=+1), which aligns with the athletes' engagement in physical exertion, which corresponds to the recognized association between warmth and optimal exercise conditions.

Finally, despite the athletes' adaptability to varying conditions, the application of Griffiths' method frequently yields neutral temperature recommendations that fall below the lower limit defined by the adaptive model. Given the evident disparities in preferences and responses between athletes and sedentary individuals, future research should focus on understanding the adaptive capacities that pertain specifically to sports facilities. The distinct requirements of athletes necessitate a focused exploration to enhance their training environments effectively.

6. Acknowledgements

This research has been developed as a result of the collaboration with the fencing club Club Scherma Pisa Antonio Di Ciolo. The authors gratefully acknowledge the availability of the trainers and of all the athletes taking part in this research.

7. References

Ainsworth, B., Haskell, W. L., Herrmann, S. D., Meckes, N., BASSETT, D. R. JR., Tudor-Locke, C., Greer, J. L., Vezina, J., Whitt-Glover, M. C., & Leon, A. S. (2011). 2011 Compendium of Physical Activities: A Second Update of Codes and MET Values. Medicine & Science in Sports & Exercise, 43(8). https://journals.lww.com/acsm-msse/Fulltext/2011/08000/2011_Compendium_of_Physical_Activities__A_Second.25.aspx

Andrade, A., Dominski, F. H., & Coimbra, D. R. (2017). Scientific production on indoor air quality of environments used for physical exercise and sports practice: Bibliometric analysis. Journal of Environmental Management, 196, 188–200. https://doi.org/10.1016/j.jenvman.2017.03.001

Berquist, J., Ouf, M. M., & O'Brien, W. (2019). A method to conduct longitudinal studies on indoor environmental quality and perceived occupant comfort. Building and Environment, 150, 88–98. https://doi.org/10.1016/j.buildenv.2018.12.064

Bluyssen, P. (2019). The need for understanding the indoor environmental factors and its effects on occupants through an integrated analysis. IOP Conference Series: Materials Science and Engineering, 609, 022001. https://doi.org/10.1088/1757-899X/609/2/022001

Braniš, M., Šafránek, J., & Hytychová, A. (2009). Exposure of children to airborne particulate matter of different size fractions during indoor physical education at school. Building and Environment, 44(6), 1246–1252. https://doi.org/10.1016/j.buildenv.2008.09.010

Cheung, T., Schiavon, S., Parkinson, T., Li, P., & Brager, G. (2019). Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II. Building and Environment, 153, 205– 217. https://doi.org/10.1016/j.buildenv.2019.01.055

Cianfanelli, C., Valeriani, F., Santucci, S., Giampaoli, S., Gianfranceschi, G., Nicastro, A., Borioni, F., Robaud,

G., Mucci, N., & Romano Spica, V. (2016). Environmental Quality in Sports Facilities: Perception and Indoor Air Quality. Journal of Physical Education and Sports Management, 3. https://doi.org/10.15640/jpesm.v3n2a4

Doherty, T. J., & Arens, E. (1988). Evaluation of the physiological bases of thermal comfort models (Vol. 94).

EN 16798-1. Energy performance of buildings—Ventilation for buildings—Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, (2019).

Fantozzi, F., & Lamberti, G. (2019). Determination of Thermal Comfort in Indoor Sport Facilities Located in Moderate Environments: An Overview. 10(12), 769. https://doi.org/10.3390/atmos10120769

Fletcher, M. J., Glew, D. W., Hardy, A., & Gorse, C. (2020). A modified approach to metabolic rate determination for thermal comfort prediction during high metabolic rate activities. Building and Environment, 185, 107302. https://doi.org/10.1016/j.buildenv.2020.107302

Humphreys, M., & Nicol, F. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy and Buildings, 34, 667–684. https://doi.org/10.1016/S0378-7788(02)00018-X

ISO 10551. Ergonomics of the physical environment—Subjective judgement scales for assessing physical environments, (2019).

ISO 7726. Ergonomics of the thermal environment – Instruments for measuring physical quantities, (2001).

ISO 7730. Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, (2006).

ISO 8996. Ergonomics of the thermal environment—Determination of metabolic rate, (2005).

ISO 9920. Ergonomics of the thermal environment. Estimation of thermal insulation and water vapour resistance of a clothing ensemble, (2009).

Khalil, E. E., & Al-hababi, T. (2016). Numerical Investigations of Flow Patterns and Thermal Comfort in AirConditioned Gymnastic Sport Facility. https://doi.org/10.2514/6.2016-0996

Kisilewicz, T., & Dudzińska, A. (2015). Summer overheating of a passive sports hall building. Archives of Civil and Mechanical Engineering, 15(4), 1193–1201. https://doi.org/10.1016/j.acme.2015.03.002

Koelblen, B., Psikuta, A., Bogdan, A., Annaheim, S., & Rossi, R. M. (2018). Thermal sensation models: Validation and sensitivity towards thermo-physiological parameters. Building and Environment, 130, 200–211. https://doi.org/10.1016/j.buildenv.2017.12.020

Lamberti, G., Leccese, F., Salvadori, G., Contrada, F., & Kindinis, A. (2023). Investigating the effects of climate on thermal adaptation: A comparative field study in naturally ventilated university classrooms. Energy and Buildings, 294, 113227. https://doi.org/10.1016/j.enbuild.2023.113227

Lamberti, G., Leccese, F., Salvadori, G., & Fantozzi, F. (2020). Effect of Exercise on Athletes Performing in Fencing Uniforms: Methodology and Preliminary Results of the Use of Infrared Thermography to Detect the Thermal Behaviour of Fencers. 10(3296). https://doi.org/10.3390/app10093296

Lebon, M., Fellouah, H., Galanis, N., Limane, A., & Guerfala, N. (2017). Numerical analysis and field measurements of the airflow patterns and thermal comfort in an indoor swimming pool: A case study.

Energy Efficiency, 10(3), 527–548. https://doi.org/10.1007/s12053-016-9469-0

Leon Paul. (2016). Hot fencer in uniform! https://www.leonpaul.com/blog/hot-fencer-in-uniform/

Lou, H., & Ou, D. (2019). A comparative field study of indoor environmental quality in two types of open-plan offices: Open-plan administrative offices and open-plan research offices. Building and Environment, 148, 394–404. https://doi.org/10.1016/j.buildenv.2018.11.022

Nicol, F., Humphreys, M., & S., R. (2012). Adaptive Thermal Comfort: Principles and Practice. In Adaptive Thermal Comfort: Principles and Practice (p. 175). Routledge. https://doi.org/10.4324/9780203123010

Peeters, L., Dear, R. de, Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. Applied Energy, 86(5), 772–780. https://doi.org/10.1016/j.apenergy.2008.07.011

Rajagopalan, P., & Luther, M. B. (2013). Thermal and ventilation performance of a naturally ventilated sports hall within an aquatic centre. Energy and Buildings, 58, 111–122. https://doi.org/10.1016/j.enbuild.2012.11.022

Revel, G. M., & Arnesano, M. (2014a). Measuring overall thermal comfort to balance energy use in sports facilities. Measurement, 55, 382–393. https://doi.org/10.1016/j.measurement.2014.05.027

Revel, G. M., & Arnesano, M. (2014b). Perception of the thermal environment in sports facilities through subjective approach. Building and Environment, 77, 12–19. https://doi.org/10.1016/j.buildenv.2014.03.017

Rupp, R. F., Kim, J., Ghisi, E., & de Dear, R. (2019). Thermal sensitivity of occupants in different building typologies: The Griffiths Constant is a Variable. Energy and Buildings, 200, 11–20. https://doi.org/10.1016/j.enbuild.2019.07.048

Singh, M. K., Mahapatra, S., & Atreya, S. K. (2011). Adaptive thermal comfort model for different climatic zones of North-East India. Applied Energy, 88(7), 2420–2428. https://doi.org/10.1016/j.apenergy.2011.01.019

Torriani, G., Lamberti, G., Salvadori, G., Fantozzi, F., & Babich, F. (2023). Thermal comfort and adaptive capacities: Differences among students at various school stages. Building and Environment, 237, 110340. https://doi.org/10.1016/j.buildenv.2023.110340

Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications – A review. Applied Energy, 115, 164–173. https://doi.org/10.1016/j.apenergy.2013.10.062

Zhai, Y., Elsworth, C., Arens, E., Zhang, H., Zhang, Y., & Zhao, L. (2015). Using air movement for comfort during moderate exercise. Building and Environment, 94, 344–352. https://doi.org/10.1016/j.buildenv.2015.08.026

Zora, S., Balci, G. A., Colakoglu, M., & Basaran, T. (2017). Associations between Thermal and Physiological Responses of Human Body during Exercise. Sports (Basel, Switzerland), 5(4), 97. PubMed. https://doi.org/10.3390/sports5040097