FINAL REPORT

1 General Information

DFG reference number: WA 1155/7-3

Project number: 443126640

Project title: Investigation of the Effect of Radiant Heat Flux on Thermal Sensation and Thermal Comfort

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Name(s) of the cooperation partners:

Reporting period (entire funding period): 1.6 years (19 months)

2 Summary

The research project investigated the impact of radiant heat transfer on thermal sensation and comfort. Unlike conventional radiators, radiant heating systems provide a substantial proportion of heat through long wave radiation and can achieve a high level of thermal comfort. The project aimed to improve the existing UC Berkeley thermal comfort model by better representing radiant heat exchange between individual body parts and their thermal environment. This addresses an important limitation of the most widely applied comfort models, including PMV/PPD, which were derived for steady, near uniform conditions and treat radiant asymmetry only through empirical dissatisfaction limits [1-3].
Datasets obtained from neutral and localized radiant heating experiments were used to improve the Berkeley sub-models for predicting local thermal sensation and local thermal comfort. In addition, two further experimental series were conducted to validate the improved Berkeley model using datasets that were not included in the model development process. The first validation series investigated asymmetric thermal environments representing typical sum-

mer and winter indoor conditions with radiant temperature asymmetries between room surfaces. The second investigated transient thermal environments in which participants moved between rooms with different thermal conditions.

The validation demonstrated that the improved Berkeley model predicts local thermal sensation and local thermal comfort more accurately than the existing Berkeley model under both asymmetric and transient conditions. The project therefore provides a more reliable basis for evaluating thermal comfort in buildings equipped with radiant heating systems and in other environments characterized by thermal asymmetries or transient thermal exposures.

In addition to improving the existing Berkeley model, the project showed that localized radiant heating can substantially reduce gender differences in skin temperature, local and overall thermal sensation, and thermal comfort under cool indoor conditions. Furthermore, the project generated a comprehensive experimental database, validated model coefficients, and reusable statistical analysis procedures that provide a valuable foundation for future research on radiant heating, personalized environmental control, and the design of human thermal environments.

2.1 Zusammenfassung

Das Forschungsprojekt untersuchte den Einfluss des Strahlungswärmeaustauschs auf das thermische Empfinden und den thermischen Komfort. Strahlungsheizsysteme übertragen einen wesentlichen Teil der Wärme über langwellige Strahlung und können dadurch ein hohes Komfortniveau ermöglichen. Ziel des Projekts war es, das bestehende thermische Komfortmodell der UC Berkeley so weiterzuentwickeln, dass der Strahlungswärmeaustausch zwischen einzelnen Körperteilen und ihrer thermischen Umgebung genauer abgebildet wird. Damit wird eine wichtige Einschränkung verbreiteter Komfortmodelle wie PMV/PPD adressiert, die für stationäre, annähernd homogene Bedingungen entwickelt wurden und Strahlungsasymmetrien nur über empirische Unzufriedenheitsgrenzen berücksichtigen [1–3].

Für die Weiterentwicklung der Berkeley-Teilmodelle zur Vorhersage des lokalen thermischen Empfindens und Komforts wurden Daten aus Neutralitätsversuchen und Experimenten mit lokalisierter Strahlungsheizung verwendet. Die Validierung erfolgte mit unabhängigen Datensätzen aus zwei weiteren Versuchsreihen. Untersucht wurden zum einen asymmetrische thermische Umgebungen mit sommerlichen und winterlichen Randbedingungen, zum anderen transiente Situationen, in denen sich Versuchspersonen zwischen unterschiedlich temperierten Räumen bewegten.

Die Ergebnisse zeigen, dass das weiterentwickelte Berkeley-Modell das lokale thermische Empfinden und den lokalen thermischen Komfort unter asymmetrischen und transienten Bedingungen genauer vorhersagt als das bestehende Modell. Es bietet damit eine verlässlichere

Grundlage für die Bewertung von Gebäuden mit Strahlungsheizsystemen sowie weiterer thermisch nicht homogener oder zeitlich veränderlicher Umgebungen.
Darüber hinaus zeigte das Projekt, dass lokalisierte Strahlungsheizung unter kühlen Innenraumbedingungen geschlechtsspezifische Unterschiede bei Hauttemperatur, lokalem und gesamtkörperbezogenem thermischem Empfinden sowie thermischem Komfort deutlich reduzieren kann. Zudem entstanden eine umfassende experimentelle Datenbasis, validierte Modellkoeffizienten und wiederverwendbare statistische Auswertungsverfahren als Grundlage für zukünftige Arbeiten zu Strahlungsheizung und personalisierter Umgebungskonditionierung.

3 Progress Report

The previous project phase (WA 1155/7-1) established the experimental basis for improving the existing UC Berkeley thermal comfort model by determining local neutral skin temperature setpoints and collecting detailed measurement data during localized radiant heating experiments. The present project focused on the statistical evaluation of these datasets, the improvement of the Berkeley sub-models for local thermal sensation and local thermal comfort, and the validation of the improved Berkeley model under independent thermal environments.
Several models have been developed by different international authors to predict local thermal sensation and comfort under nonuniform environments. Among them, the UC Berkeley thermal comfort model developed by Zhang [4] is currently one of the most comprehensive physiological models available. It predicts local thermal sensation based on local skin temperature, mean skin temperature, core temperature, and their temporal changes and has therefore become the basis for numerous subsequent studies [5–7]. Nevertheless, the original model coefficients were primarily derived from experiments involving local convective heating and cooling, while only limited experimental evidence is available for localized radiant heating.
In this project, the datasets obtained from the neutral and localized radiant heating experiments were used for model development. The neutral experiment provided new local neutral skin temperature setpoints, while the localized radiant heating dataset was used to find the Berkeley sub-models' new coefficients for local thermal sensation and local thermal comfort using nonlinear regression techniques.
To evaluate the general applicability of the improved Berkeley model, two independent validation studies were conducted. The first investigated asymmetric thermal environments representing typical summer and winter indoor conditions created by different combinations of heated and cooled room surfaces. The second investigated transient thermal environments in which participants moved between rooms with different thermal conditions. These validation

datasets were not used during coefficient estimation, allowing an independent assessment of model performance under realistic nonuniform thermal environments.

Model development began with determining new local neutral skin temperature setpoints under controlled thermally neutral conditions. These temperatures represent the physiological reference state of individual body parts and constitute one of the key input parameters of the local thermal sensation sub-model.

The analysis demonstrated differences between the neutral skin temperatures obtained in the present study and those reported in the original Berkeley model. The largest deviations were observed for peripheral body regions such as the hands and feet, whereas smaller differences were found for central body parts. These results indicate that local neutral skin temperatures are influenced by experimental conditions and participant characteristics. The newly determined neutral skin temperatures were subsequently adopted as reference values for all further model development.

Following the determination of the local neutral skin temperature setpoints, the existing Berkeley local thermal sensation sub-model was evaluated using the model development dataset (Figure 1). Although the original model reproduced the general trends of human thermal perception, systematic deviations were observed for several body parts, indicating that improvement of the model coefficients was required.

To improve the predictive capability of the Berkeley local thermal sensation sub-model, all coefficients were recalculated using the model development dataset. The statistical analysis was performed using nonlinear mixed-effects regression to account for repeated measurements obtained from individual participants while estimating common coefficients for each body part. Standard nonlinear regression assumes independent observations, which is violated by the repeated measures design of the experiments; participants with more sessions would then disproportionately influence the fit and bias the coefficients towards individual rather than population level responses. The mixed effects formulation separates inter-individual variability from the common physiological response and therefore yields more generalizable coefficients. For the local thermal comfort sub-model, a subject-weighted nonlinear regression was applied instead. The comfort function is not driven directly by skin temperature but by local and overall thermal sensation, and it contains a comparatively large number of nonlinear coefficients describing the location and level of maximum comfort, the warm and cold asymmetry, and the curvature of the response. Because of the number of coefficients, when subject level random effects were introduced, these parameters became weakly identifiable, and the nonlinear mixed effects estimation did not converge to a stable solution. Observation weights were therefore assigned at the participant level, so that participants contributing more repeated measurements did not dominate the fit. This retains the objective of the mixed effects approach while remaining numerically stable for the more strongly nonlinear comfort function. The resulting coefficients differed from those of the original Berkeley model for most body parts, indicating that localized radiant heating produces thermal responses that cannot be fully represented using coefficients derived from convective heating experiments. Together with the newly determined neutral skin temperature setpoints, the new coefficients provide a substantially improved physiological description of local thermal sensation during radiant heat exposure.

To evaluate the improved Berkeley local thermal sensation sub-model, the prediction accuracy of the original and improved models was compared using the model development dataset. The recalibrated model consistently reduced both the mean absolute error (MAE) and the root mean square error (RMSE) for nearly all investigated body parts while simultaneously reducing systematic prediction bias. The largest improvements were observed for the head, neck, chest, pelvis, face and back, where the original Berkeley model showed the greatest deviations from the measured responses.

Overall, the improved Berkeley local thermal sensation sub-model substantially improved the prediction of local thermal sensation under localized radiant heating conditions.

The existing Berkeley local thermal comfort sub-model was subsequently investigated using the same model development dataset (Figure 2). Since local thermal comfort depends not only on local thermal sensation but also on overall thermal sensation, a separate weighted nonlinear regression procedure was applied to estimate the new comfort coefficients while accounting for the unequal distribution of measurements among participants.

The statistical approach produced a complete set of new coefficients describing the relationship between local thermal sensation, overall thermal sensation and perceived local thermal comfort. Compared with the existing Berkeley model, the improved coefficients more accurately represented participants' comfort responses under localized radiant heating conditions. The improved Berkeley local thermal comfort sub-model demonstrated a clear reduction in prediction errors compared with the existing Berkeley model and provided a substantially improved description of local comfort under nonuniform radiant environments. Together, the improved Berkeley local thermal sensation and local thermal comfort sub-models represent the main scientific achievement of the project.

An important objective of the project was to demonstrate that the improved Berkeley model is not only capable of reproducing the calibration data but also remains applicable under independent thermal environments. For this purpose, validation experimental datasets that were completely excluded from the regression process were used. These datasets came from additional experiments: two asymmetric room conditions typical for summer and winter (warm wall with cooled ceiling; cold wall with heated ceiling), and transient room change experiments (cold–warm–cold and warm–cold–warm). As most participants differed from those in the model development experiments, the validation basis was largely independent.

Model performance was assessed using the mean absolute error (MAE), root mean square error (RMSE), mean prediction bias, and the percentage of predictions within predefined error limits. The improved Berkeley local thermal sensation sub-model was first evaluated using the independent validation datasets.

The validation results demonstrated a consistent improvement over the existing Berkeley model under both asymmetric and transient thermal environments. Under asymmetric conditions, the improved model reduced the overall prediction error while simultaneously increasing the proportion of predictions within one thermal sensation scale unit. Comparable improvements were obtained for the transient experiments, indicating that the improved coefficients remain applicable under changing thermal environments despite being derived from localized radiant heating experiments.

The improvement was observed for all investigated body parts (Figure 3). The largest reductions in prediction error occurred for the head, neck, chest, hand, foot, lower arm, and back. The overall reduction in MAE, RMSE demonstrates that the improved model more accurately represents local thermal sensation across a broad range of thermal environments.

The improved local thermal comfort sub-model showed the same trend for most body parts (Figure 4). MAE and systematic bias decreased and the proportion of predictions within ±0.5 and ±1.0 comfort scale units increased relative to the Berkeley model. The largest improvements were obtained for the hand, lower arm, lower leg, back and upper leg, whereas the face, and head showed no improvement. These indicate that the relationship between local thermal sensation, overall thermal sensation and local thermal comfort remains valid even under thermal conditions that were not included during coefficient estimation

The validation results demonstrate that the improved Berkeley local thermal sensation and local thermal comfort sub-models successfully predict thermal responses under independent asymmetric and transient environments. This independent validation provides strong evidence that the proposed model improvements increase the applicability of the UC Berkeley thermal comfort model for evaluating asymmetric temperature conditions in practical building applications. The overall validation results are summarized in Table 1.

In addition to model development, the project investigated whether localized radiant heating could reduce gender differences in thermal perception. Previous studies have consistently reported that women experience lower skin temperatures and greater thermal discomfort than men under cool indoor conditions [8]. Our neutral and local heating experiments' results demonstrated that localized radiant heating substantially reduced these differences. While baseline measurements showed moderate to large gender differences in skin temperature,

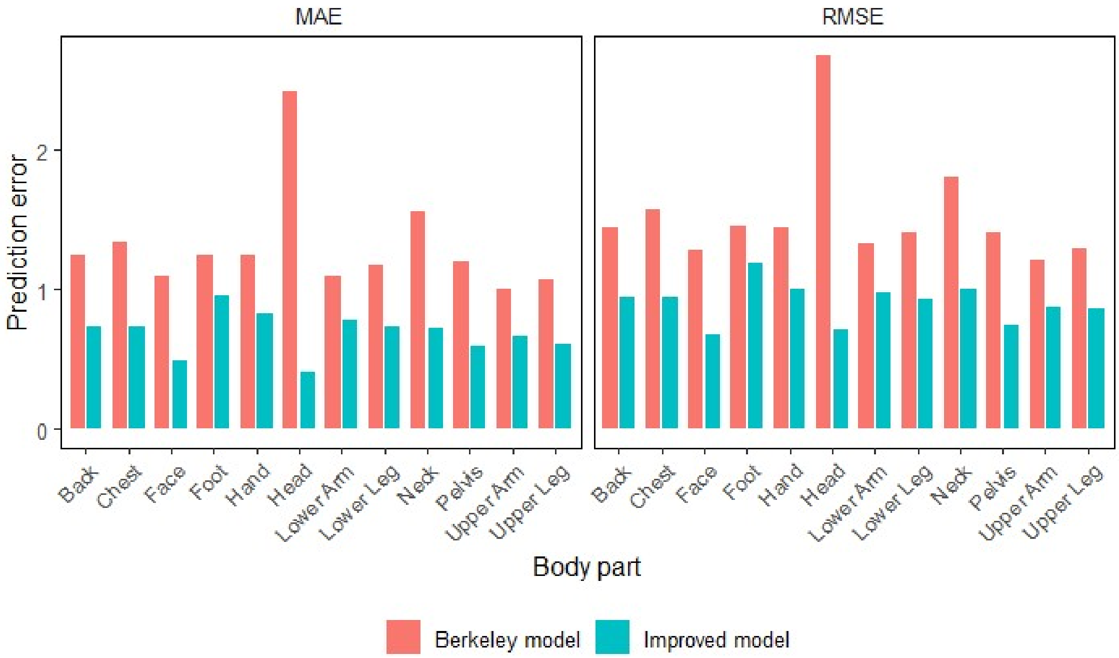

Figure 1. MAE and RMSE comparison between improved and existing Berkeley local sensation sub-model based on model development dataset

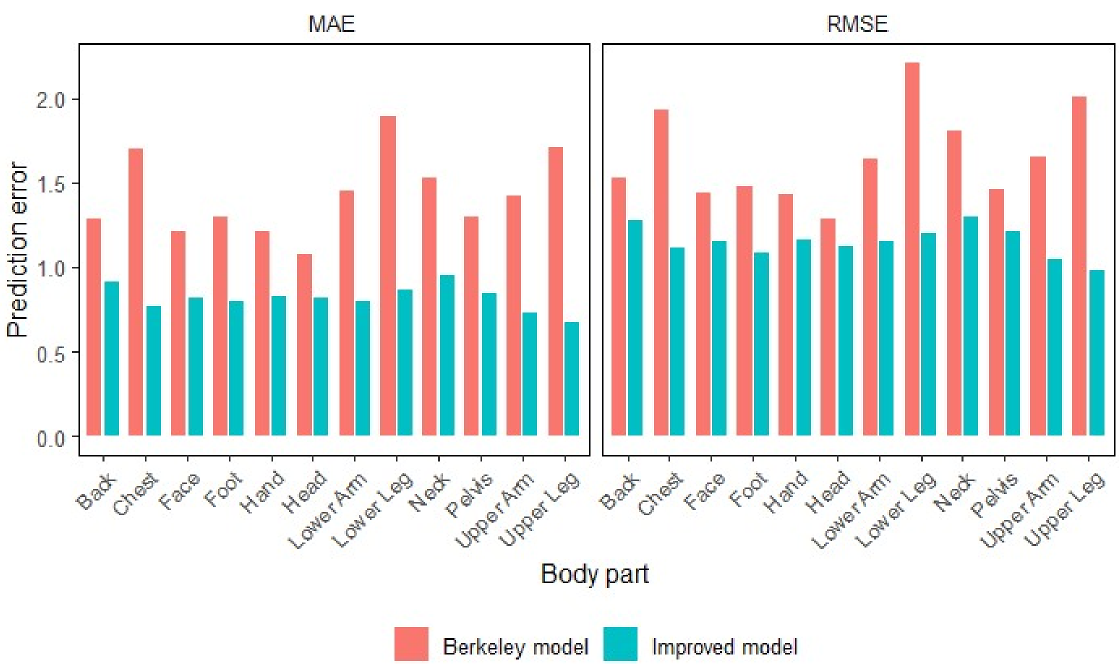

Figure 2. MAE and RMSE comparison between improved and existing Berkeley local comfort sub-model based on model development dataset

Table 1. Performance comparison between the improved and existing Berkeley models

	Experiment	Model	Mean error bias	MAE	RMSE	Within ±0.5 (%)	Within ±1.0 (%)
Sensation	Asymmetric	Improved	0.26	0.83	1.02	38	67
		Berkeley	0.30	1.18	1.44	26	49
	Transient	Improved	0.52	0.84	1.03	37	65
		Berkeley	0.34	1.12	1.38	28	52
Comfort	Asymmetric	Improved	0.15	0.89	1.11	41	66
		Berkeley	-0.37	1.12	1.36	28	53
	Transient	Improved	-0.01	0.82	1.06	48	70
		Berkeley	-0.50	1.13	1.40	30	55

local thermal sensation and overall thermal sensation, these differences became small or negligible after localized heating was applied. The strongest improvements in overall sensation and comfort were obtained by heating the pelvis and chest, indicating that these body parts have a large influence on overall thermal perception. These findings demonstrate that localized radiant heating represents an effective strategy for improving comfort while simultaneously reducing gender related differences in thermal responses [8].

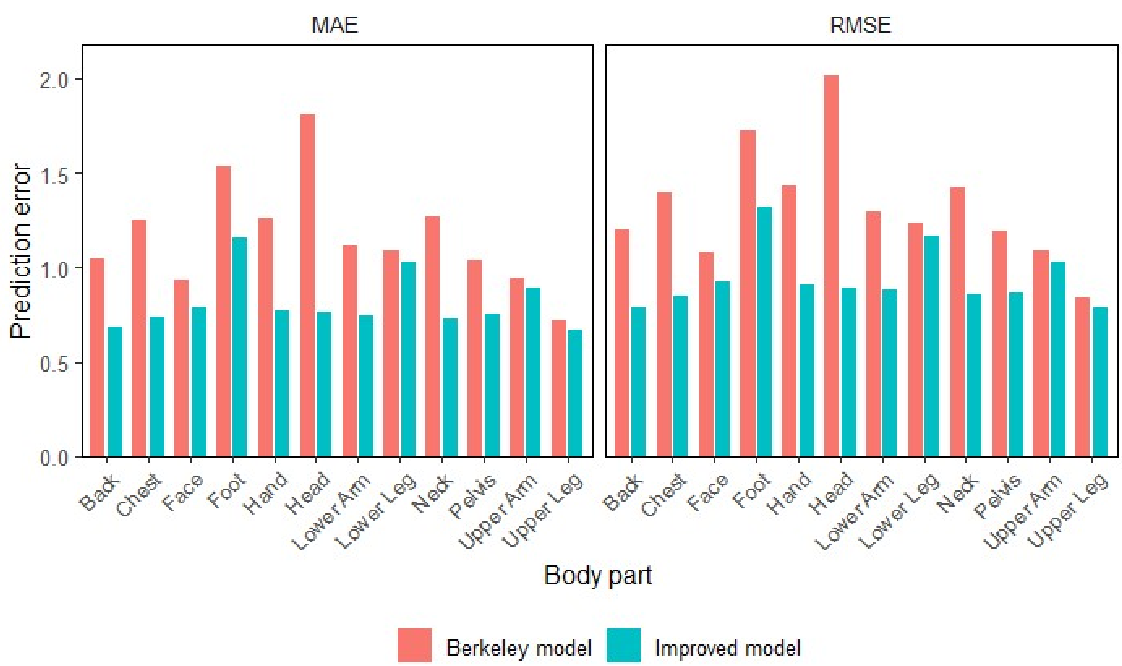

Figure 3. MAE and RMSE comparison between improved and existing Berkeley local sensation sub-model based on validation dataset

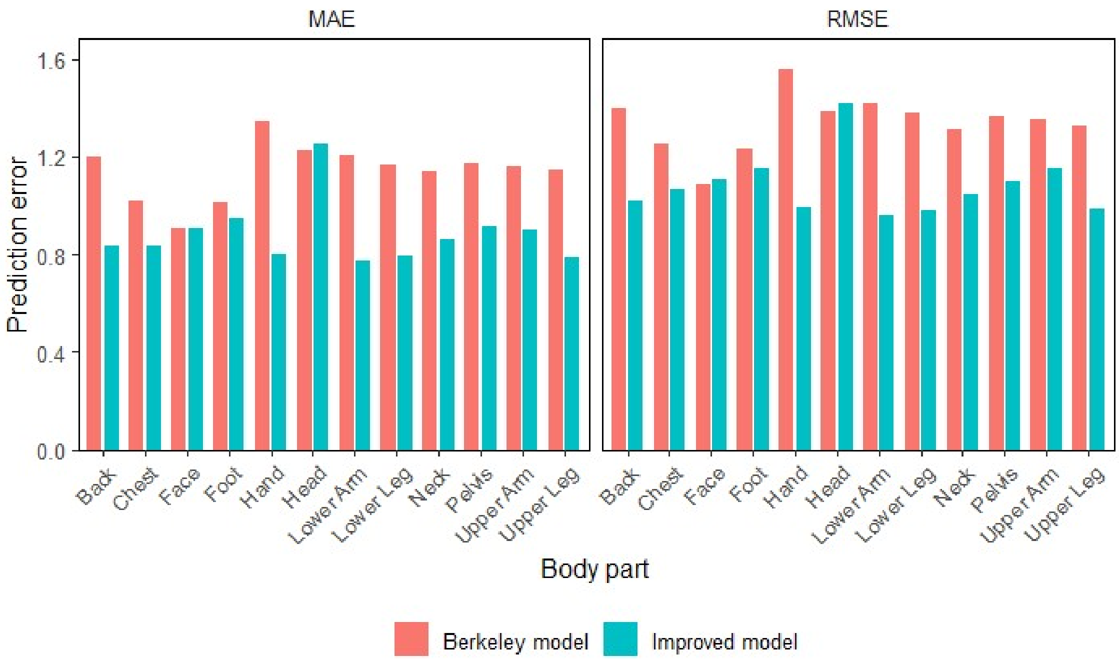

Figure 4. MAE and RMSE comparison between improved and existing Berkeley local comfort sub-model based on validation dataset

Overall, the project achieved its objective of improving the UC Berkeley local thermal sensation and comfort sub-models for localized radiant heating applications. In addition to the improved model coefficients, the project generated a comprehensive experimental database and reusable statistical analysis procedures that provide a valuable foundation for future research on radiant heating, personalized environmental control, and building design.

3.1 Bibliography

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[2] P.O. Fanger, et al., “Comfort limits for asymmetric thermal radiation, ” Energy and buildings, vol. 8(3), p. 225-236, 1985.

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[7] Y. Tang, et al., “Evaluation and improvement of the Berkeley local thermal sensation model,” Building and Environment, vol. 289, p. 114065, 2026.
[8] S. M. Hooshmand, et al., “Effects of localized radiant heating on gender differences in skin temperature, thermal sensation, and comfort,” Journal of Building Physics, 2026.

4 Published Project Results

4.1 Category A – Articles in peer-reviewed journals, contributions to peer-reviewed conferences or to anthology volumes, and book publications

-S.M. Hooshmand, et al., "A review of local radiant heating systems and their effects on thermal comfort and sensation," Energy and Buildings, 2023, 113331. DOI:10.1016/j.enbuild.2023.113331
-S. M. Hooshmand, et al., “Effects of localized radiant heating on gender differences in skin temperature, thermal sensation, and comfort,” Journal of Building Physics, 2026. DOI:10.1177/17442591261447477
-S.M. Hooshmand, et al., "Designing Local Radiant Heating Devices for Different Body Parts: Effects on Skin Temperature," The 8th International ICARB Conference, Edinburgh, 2023.
-S.M. Hooshmand, et al., "Maximizing Comfort: Comparative Analysis of Key Body Parts in Local Radiant Heating Systems," The 18th International Conference of the International Society of Indoor Air Quality & Climate, Hawaii, 2024.
-S.M. Hooshmand, et al., "Tailored Comfort: Revealing Targeted Body Parts for Energy-Efficient Localized Heating and Cooling Systems," IABP 2024. Lecture Notes in Civil Engineering, vol 555. Springer, Singapore. 2025. DOI:10.1007/978-981-97-8317-5_26
-S.M. Hooshmand, et al., “Localized Thermal Sensation and Comfort: A Study on Thermal Neutrality Ranges Using Skin Temperature Set Points,” ASHRAE Annual Conference, 2025.
-S.M. Hooshmand, et al., “Experimental Investigation of Gender Differences in Skin Temperature and Local Thermal Comfort,” Proceedings of CESBP 2025 - 6th Central European Symposium on Building Physics. 751-760. DOI:10.1007/978-3-032-14019-7_55.

4.2 Category B – Any other form of published results

- A. Rezaee Parsa, et al., “Prediction of Overall Thermal Comfort of Radiant Heating Systems Using Experimental Local Comfort Data- A Machine Learning Approach,” ARCC-EAAE International Conference, 2026.