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# Gender Differences in Thermo-Physiological Responses of Older Adults During Outdoor Activities in Summer: A Pilot Study in China's Cold Region

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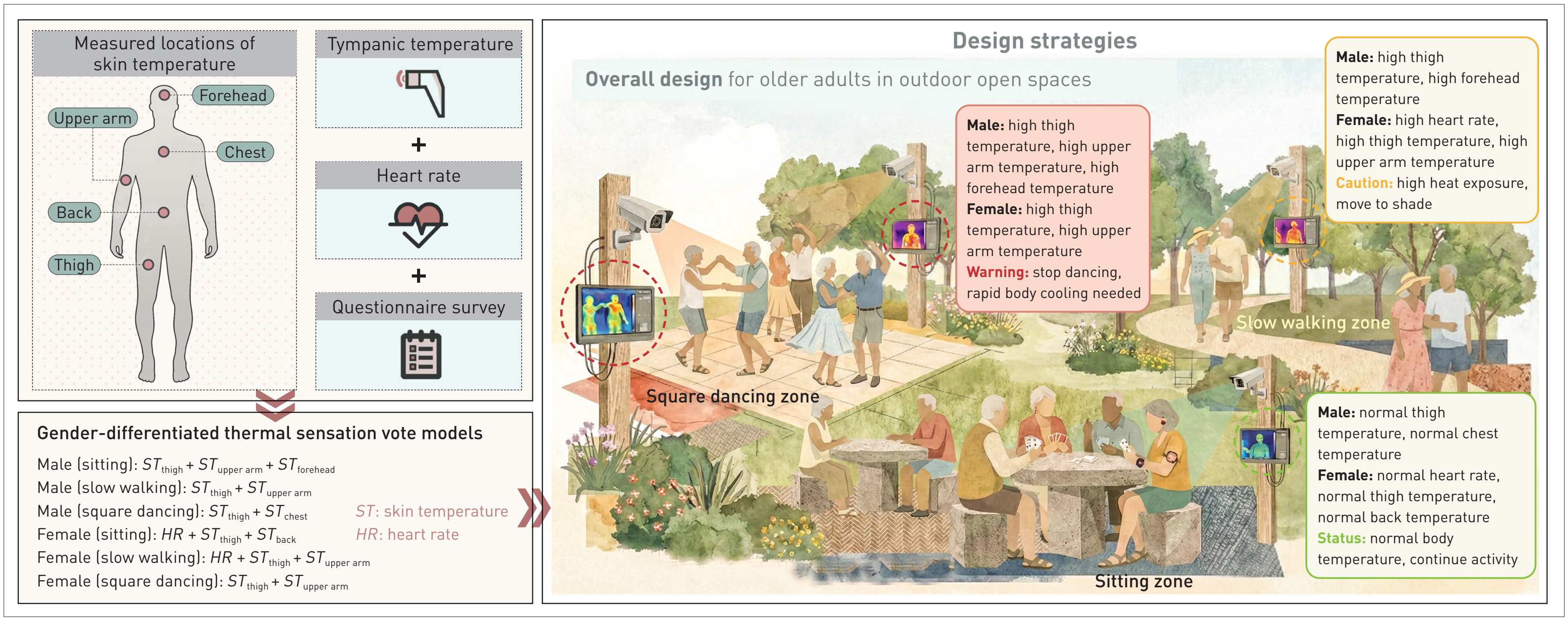
## GRAPHICAL ABSTRACT




## ABSTRACT

Global aging and intensifying heat extremes heighten outdoor thermal risk for older adults. Concurrent micrometeorological, physiological, and thermal-sensation data were collected from older park users in Xi'an, China, during sitting, slow walking, and square dancing. Predictors selected by statistical and machine learning methods were fed into gender-specific gradient boosting machine models of thermal sensation. Results indicated that: 1) Neutral physiological equivalent temperature (NPET) shifted markedly with activity. Older females showed lower NPET than older males during sitting, while during slow walking and square dancing, they exhibited higher NPET than males. 2) Older women maintained higher heart rates (*HR*) than men across all activities; while older men displayed a U-shaped core temperature ($T_c$) curve during slow walking. Limb skin temperatures (*ST*) exhibit more pronounced fluctuations with increasing activity intensity, whereas chest *ST* remained stable. 3) Thermal sensation vote (TSV) predictors differed by gender and activity. For men, *ST* dominated during sitting, *HR* during walking, and $T_c$ during dancing; for women, TSV correlated strongly with $ST_{upper\ arm}$ during sitting, while correlated jointly with $T_c$ and $ST_{chest}$ during square dancing. 4) The gender-specific TSV model, requiring only two to three localized physiological inputs, outperforms conventional indices in accuracy and feasibility. It directly informs age-friendly park design, enhances outdoor safety for older adults, and supports sustainable urban development.

**KEYWORDS**

Urban Open Space; Outdoor Thermal Comfort; Older Adult; Prediction Model; Thermo-physiological Characteristic

**HIGHLIGHTS**

- The gender-specific TSV model outperforms conventional indices in accuracy and feasibility
- Older men's TSV correlated with *ST* (sitting), *HR* (slow walking), and $T_c$ (square dancing)
- Older women's TSV correlated with $ST_{upper\ arm}$ when sitting, and with $T_c$ and $ST_{chest}$ when square dancing
- TSV predictors were $ST_{thigh}$ and other $ST_s$ for older men, and *HR*, $ST_{thigh}$ and other $ST_s$ for older women

**RESEARCH FUND**

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## 1 Introduction

United Nations (UN) Sustainable Development Goal 3 aims to "ensure healthy lives and promote well-being for all at all ages"[1]. However, the synergistic amplification of extreme heat events and urban heat islands—driven by accelerating urbanization and anthropogenic warming—disproportionately imperils older adults, elevating heat-related morbidity and mortality while inflicting irreversible cardiovascular, cerebrovascular, and respiratory injury[2]. Within this context, the UN Decade of Healthy Ageing (2021–2030) positions habitual outdoor physical activity as a critical modifiable determinant of healthy aging, evidenced to attenuate non-communicable disease risk, enhance physiological resilience, and ameliorate psychosocial stress and fatigue[3].

Aging attenuates autonomic and sudomotor responses, compromising the ability of older adults to sustain thermal equilibrium under heat stress[4]. Gender-specific thermoregulatory phenotypes further modulate this vulnerability. Older males, characterized by greater muscle mass and a 10% higher basal metabolic rate, generate proportionally more endogenous heat; however, their pronounced vasoconstrictor reactivity can precipitate abrupt core-temperature surges during heat waves[5]. In contrast, females present relatively thicker subcutaneous adipose tissue, which attenuates rapid conductive heat gain yet simultaneously impedes dry and evaporative heat dissipation[6]. Additionally, estrogen-mediated enhancement of cutaneous vasoconstrictor sensitivity attenuates skin blood flow in response to mild cold, further reducing heat-loss capacity[7]. Consequently, gender-specific physiology drives divergent thermal trajectories by activity dose: at rest, males' higher basal metabolic rate elicits earlier warmth perception[8]; during moderate-to-vigorous exertion, their attenuated vasodilation precipitates steep core temperature ($T_c$) rises[9], whereas females' adipose shell resists heat loss and delays dissipation under high metabolic loads[10]. Activity intensity therefore magnifies geriatric thermoregulatory dimorphism and associated risk, but systematic gender-disaggregated evidence across intensities remains sparse.

Empirical evidence confirms that the above physiological dimorphisms translate into systematic gender differences in thermal perception and tolerance among older adults. Heat-related mortality rises more steeply for older women than for men in hot–humid climates[11]. Fei Yao et al. observed thermal neutrality in 30% of older women versus 25% of older men during summer, and in 28% versus 18% during winter, indicating a higher propensity for females to achieve comfort[12]. Reflecting these disparities, gender-specific predictive frameworks have emerged: Chien Hung Tung et al. derived neutral physiological equivalent temperature (PET) thresholds of 25.2°C for women and 26.1°C for men via bin-wise linear regression[13], whereas Xin Chen et al. embedded gender-specific distributions of adiposity and muscle mass into an outdoor thermoregulation model[14].

Extant outdoor research juxtaposes old and young cohorts, yet gender differences within aging populations and how these are affected by metabolic load remain empirically unexplored. Thermal comfort in this population is typically assessed using energy-balance, adaptive, or thermoregulation models that require many coupled inputs, limiting rapid application. Existing predictors are largely gender-aggregated and calibrated to a single activity level, offering little guidance for men and women across varying activity intensities. To address these gaps, we systematically examine the links between thermal sensation and key physiological parameters in older men and women at multiple activity intensities and develop fast, accurate, gender-specific prediction models applicable across activity levels.

This study investigated outdoor thermal perception and concomitant physiological responses in older males and females at three metabolic intensities, represented by sitting, walking, and dancing in urban parks of Xi'an, China. Synchronous micrometeorological monitoring, wearable physiological sensing, and structured questionnaires were employed. The study has three aims: 1) quantify neutral PET (NPET) and its range (NPETR) for each gender–activity combination; 2) characterize gender-specific thermophysiological response patterns across activity levels; and 3) identify the minimal set of physiological predictors to construct gender-differentiated thermal sensation vote (TSV) models for older park users. The findings delineate gender-based divergences in thermal perception and regulation, providing evidence-based thresholds for age-inclusive, thermally safe urban design under intensifying heat.

## 2 Methods

### 2.1 Study Sites

The field experiment was carried out in an urban park (6 $hm^2$) in Xi'an, China, which contains heterogeneous micro-environments frequently used by older adults. Two representative settings were selected based on visitor counts, spatial configuration, and sky view factor (SVF): an open square site and a leisure square site (Fig. 1). As local thermal conditions are determined by the air temperature within 10 ~ 150 m of the measurement centroid[15–16], landscape composition was quantified for a 10-meter radius buffer centered on a measurement point[17] within each square. SVF was derived from upward-facing fisheye images analyzed in RayMan (Table 1).

### 2.2 Experimental Design

2.2.1 Activity Intensity

Following the metabolic equivalent of task (MET) taxonomy, activities were classified as light (< 3 MET), moderate (3 ~ 6 MET), and vigorous (> 6 MET)[18]. Because vigorous exertion poses acute health risks to older adults during summer heat[19], only light- and moderate-intensity behaviors commonly observed in parks in Xi'an were examined: sitting (chatting/viewing the landscape, 1.0 MET), slow walking (≤ 3.2 km/h, 2.5 MET), and square dancing (4.5 MET)[18].

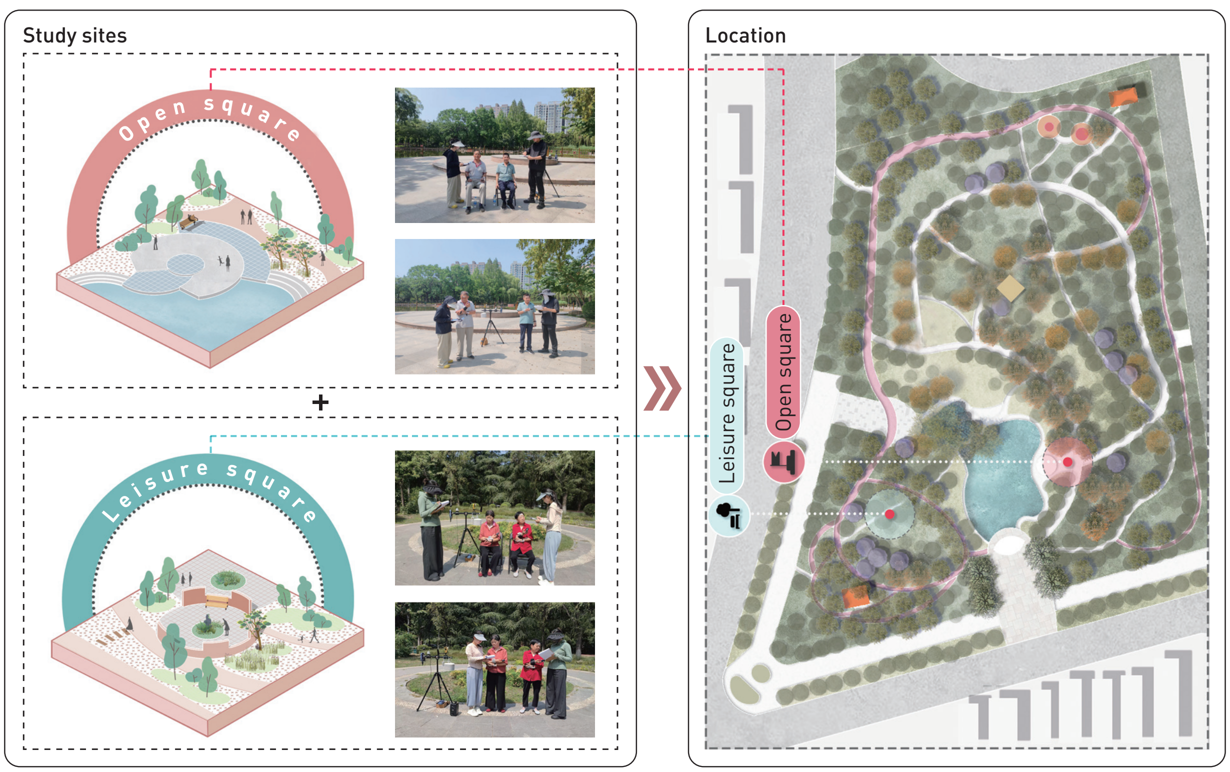


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**Fig. 1** Site locations and surrounding environments.

**Table 1: Descriptions and spatial characteristics of the study sites**

| Site | Spatial characteristics | SVF |
|---|---|---|
| Open square site | This site is situated next to a scenic lake within an open square; the primary landscape features are hard paving (62%), trees (13%), benches (4%), and water bodies (21%) |  0.63 |
| Leisure square site | This site is a sheltered leisure area enclosed by a landscape wall; the primary landscape features are hard paving (46%), a central flower bed (18%), benches (6%), and trees (30%) |  0.30 |

**NOTE**
The percentages of landscape composition were quantified through field surveys within the 10-meter radius plots.

**Table 2: Instrument information of physiological measurements**

| Variable | Instrument | Measurement range | Measurement accuracy |
|---|---|---|---|
| $HR$ | Philips- DB12 pulse oximeter | 30 ~ 250 bpm | ±3 bpm |
| $T_c$ | Braun- IRT6520 ear thermometer | 35.0 ~ 42.0°C | ±0.3°C |
| $ST$ | iButton DS1922L skin thermometer | −40.0 ~ 85.0°C | ±0.1°C |

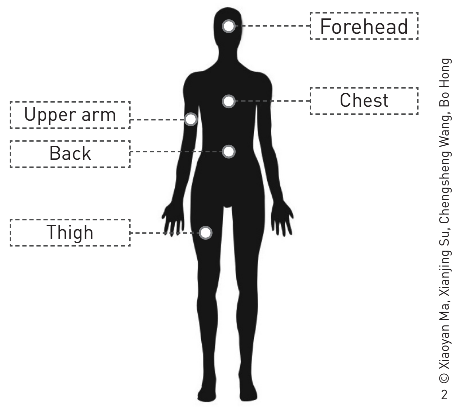



**Fig. 2** Measured spots of skin temperature.

2.2.2 Questionnaire

The questionnaire comprised two sections. Section 1 captured gender, age, stature, body mass, clothing insulation[20], and local residence duration. Section 2 recorded TSV on the 7-point ASHRAE scale: cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2), and hot (+3)[20].

2.2.3 Physiological Measurements

Physiological monitoring comprised heart rate ($HR$), core temperature ($T_c$), and five-site skin temperature ($ST$) (Table 2). $ST$ sensors were affixed to the forehead, chest, upper arm, back, and thigh (Fig. 2). Mean skin temperature ($ST_{mean}$) was computed according to Hardy and DuBois calculation formula[21]:

$$ST_{\text{mean}} = 0.15 \times ST_{\text{forehead}} + 0.19 \times ST_{\text{chest}} + 0.10 \times ST_{\text{upper arm}} + 0.19 \times ST_{\text{back}} + 0.37 \times ST_{\text{thigh}} . \quad (1)$$

2.2.4 Meteorological Measurements

A meteorological station was deployed at the center of each site, with sensors mounted at a 1.1-meter height to represent human-level microclimate conditions[22]. All instruments were field-calibrated against reference equipment from the Xi'an Meteorological Bureau to ensure consistency. All parameters were logged at 1 min intervals (Table 3).

2.2.5 Experimental Procedure

The trails were conducted from 29 July to 2 August and from 5 to 8 August 2022. Each participant completed a 47-minute protocol in two stages.

1) Stage 1 (acclimatization): after fasting for at least 1 h, sensors were fitted, and participants rested quietly (either sitting or standing) for 15 min while the procedure was explained and the questionnaires were administered. $HR$ and $T_c$ were recorded between the 12th and 15th minutes, immediately followed by the first TSV survey.

2) Stage 2 (activity): participants performed one of the three 20-minute activities. $HR$ and $T_c$ were measured at five-minute intervals (5, 10, 15, and 20 min), while the participants completed the TSV questionnaires concurrently (Fig. 3).

**2.3 Basic Information of Subjects**

Older adults over 60 years old who had lived in the local area for more than one year were recruited. A total of 216 older subjects were initially recruited for this study, but one withdrew, resulting in 215 complete datasets (84 male, 131 female; ratio 1:1.56; see Table 4). The participants were allocated to three activity groups (i.e., sitting, slow walking, and square dancing) through randomization. The final distribution of the 215 participants

**Table 3: Instrument information of meteorological measurements**

| Variable | Instrument | Measurement range | Measurement accuracy |
|---|---|---|---|
| Air temperature ($T_a$) | HOBO onset U23-001 radiation-shielded logger | −40 ~ 70°C | ±0.21°C |
| Relative humidity ($RH$) | HOBO onset U23-001 radiation-shielded logger | 0 ~ 100% | ±2.5% |
| Wind speed ($V_a$) | Kestrel 5500 portable weather station | 0 ~ 40 m/s | ±0.1 m/s |
| Globe temperature ($T_g$) | Delta OHM HD 2107.2 globe thermometer and TP876.I probe (Ø50 mm) | −30 ~ 120°C | ±0.25°C |
| Global radiation ($G$) | Delta OHM HD 2102.2 pyranometer | 0.0001 ~ 1,999.9 W/m$^2$ | ≤ 3% |

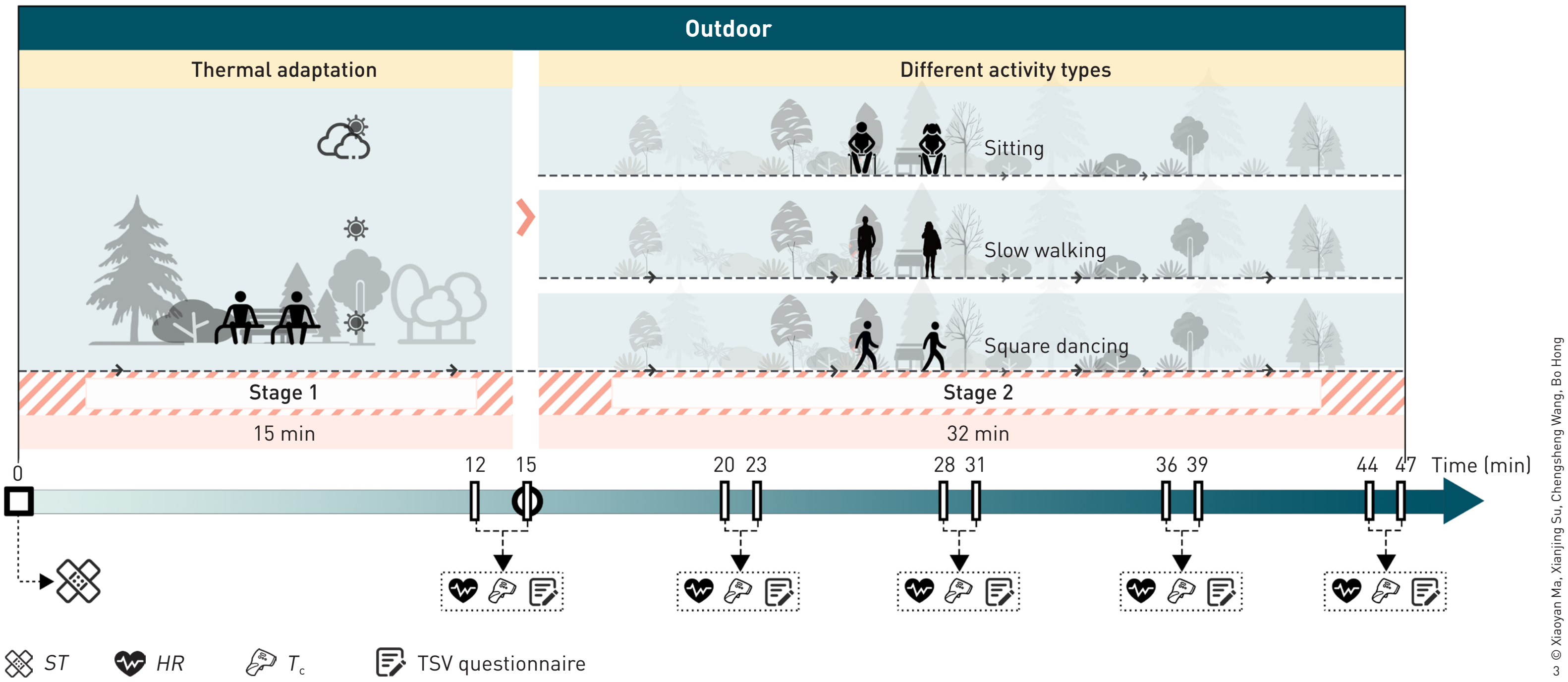



**Fig. 3** Experimental procedure.

**Table 4: Information of subjects**

| Variable | Gender | | | | | |
|---|---|---|---|---|---|---|
| | Male ($N$ = 84) | | | Female($N$ = 131) | | |
| | Min | Max | Mean ± $SD$ | Min | Max | Mean ± $SD$ |
| Age (years) | 60 | 84 | 67.8 ± 4.90 | 60 | 82 | 65.2 ± 4.55 |
| Height (cm) | 160 | 181 | 169.3 ± 5.02 | 150 | 166 | 158.8 ± 5.03 |
| Weight (kg) | 54 | 105 | 70.7 ± 7.37 | 40 | 72 | 56.4 ± 6.08 |
| Clothing insulation (clo) | 0.36 | 0.48 | 0.40 ± 0.15 | 0.39 | 0.5 | 0.42 ± 0.17 |

across these groups was balanced, with group sizes of 71, 72, and 72. All participants met strict health criteria, self-reporting as healthy with no chronic conditions affecting thermoregulation (e.g., cardiovascular disease, diabetes, thyroid disorders). To control for clothing effects, participants wore garments with comparable thermal resistance (0.35 ~ 0.50 clo).

## 2.4 Data Analysis

### 2.4.1 Thermal Index

PET, derived from the Munich Energy-balance Model for Individuals, was adopted as the thermal index. It combines $T_a$, $RH$, $V_a$, mean radiant temperature, metabolic rate, clothing insulation, age, and gender into an equivalent $T_a$ reflecting human thermal sensation[23–24]. PET was selected because it has been more widely applied in previous studies of outdoor thermal comfort among older adults compared to indices such as universal thermal climate index (UTCI) or predicted mean vote (PMV), thereby enabling more consistent comparison with existing research[12,22,25]. PET values were computed in RayMan based on simultaneous microclimate and individual measurements. Subsequently, bin-wise linear regression yielded gender-specific NPET and NPETR for each activity.

2.4.2 Model Setup

This study developed gender-specific prediction models for outdoor thermal perception in older populations through the following procedure. 1) Feature selection: predictors were identified using Spearman correlation analysis and Random Forest feature importance evaluation. Final input and output parameters were determined based on measured data, correlation strength, and feature significance. 2) Data splitting: the standardized dataset was partitioned into training (80%), validation (10%), and test (10%) subsets. The training set supported parameter learning, the validation set was used for hyperparameter optimization and overfitting prevention, and the test set provided unbiased performance assessment. 3) Model development: a Gradient Boosting Machine (GBM) was adopted to capture complex nonlinear relationships and enhance robustness to outliers. Hyperparameters were systematically tuned via grid search on the validation set. 4) Model evaluation: each candidate feature subset was evaluated using 5-fold cross-validation, with performance assessed using *RMSE*, *MSE*, and $R^2$. The optimal model was selected based on lowest *RMSE* and highest $R^2$ values.

## 3 Results

### 3.1 Meteorological Parameters

Microclimatic conditions differed significantly between the two sites due to distinct spatial and landscape characteristics. The open square site, being exposed to direct sunlight, showed higher mean $T_g$ (41.76 ~ 42.40°C) and mean $G$ (462.02 ~ 493.91 W/m$^2$) than the leisure square site, which was shaded with dense vegetation (33.93 ~ 34.55°C, 75.50 ~ 82.78 W/m$^2$). The mean $V_a$ was also higher in the open square site (0.81 ~ 0.84 m/s) because of minimal sheltering, whereas the vegetated enclosure of the leisure square resulted in lower mean $V_a$ (0.24 ~ 0.26 m/s). Despite its proximity to water, mean *RH* in the open square site (54.22% ~ 55.02%) was slightly lower than in the leisure square site (56.57% ~ 57.72%), likely due to enhanced evaporation under higher temperatures and airflow (Table 5). One-way ANOVA revealed no significant microclimatic differences among activity types in either site ($p$ > 0.05, see details in supplementary material).

### 3.2 Thermal Sensation Vote

In older males, TSV varied with exercise intensity. During 20 min sitting, TSV demonstrated minimal variation. After 15 min of slow walking, the proportion of men feeling hot increased, reaching 47% after 20 min. A similar trend was observed during square dancing, where the proportion of men feeling hot rose from 47% (5 min) to 70% (20 min), indicating a cumulative heat load effect.

Older females displayed a comparable TSV pattern. TSV responses changed little during 20 min of sitting. During slow walking, responses of slightly warm increased from 19% to 24% after 10 min, while other responses remained stable. However, after 15 min and 20 min of slow walking, the proportion of participants feeling hot surged to 49% and 54%, respectively. During square dancing, the proportion of older females feeling hot consistently escalated, peaking at 67% after 20 min (Fig. 4).

### 3.3 NPET and NPETR

NPET represents the temperature at which individuals experience thermal neutrality (neither cold nor hot). This study calculated weighted mean thermal sensation votes (MTSV) per 1°C PET increment using linear regression. From this model, we identified the NPET for older individuals (the temperature corresponding to MTSV = 0) and the NPETR (the temperature range where MTSV falls between −0.5 and 0.5).

For older men, the slopes of the linear regression equations relating MTSV to PET were 0.0985 (sitting), 0.0815 (slow walking), and 0.0689 (square dancing). Substituting MTSV = 0 into these equations, we calculated the NPET as 24.48°C (sitting), 21.38°C (slow walking), and 13.58°C (square dancing). When applying MTSV = ±0.5, the NPETR for older men ranged from 19.41°C to 29.56°C, 15.24°C to 27.51°C, and 6.32°C to 20.83°C in sitting, slow walking, and square dancing, respectively.

For older women, the slopes of the linear regression equations relating MTSV to PET were 0.0966 (sitting), 0.093 (slow walking), and 0.0722 (square dancing). Substituting MTSV = 0, the NPET was calculated as 23.98°C (sitting), 22.85°C (slow walking), and 15.01°C (square dancing). Using MTSV = ±0.5, the NPETR for older women ranged from 18.80 to 29.16°C, 17.48 to 28.23°C, and 8.09 to 21.94°C in sitting, slow walking, and square dancing, respectively (Fig. 5).

Table 5: Meteorological variables among spaces

| Meteorological variable | | Open square site | | | Leisure square site | | |
|---|---|---|---|---|---|---|---|
| | | Sitting | Slow walking | Square dancing | Sitting | Slow walking | Square dancing |
| $T_g$ (°C) | Max | 52.56 | 53.4 | 50.64 | 40.42 | 41.32 | 41.09 |
| | Min | 31.95 | 32.12 | 33.05 | 27.27 | 27.33 | 28.57 |
| | Mean ± *SD* | 41.88 ± 4.93 | 41.76 ± 4.87 | 42.40 ± 4.54 | 34.55 ± 3.38 | 33.93 ± 3.35 | 34.49 ± 3.41 |
| *RH* (%) | Max | 67.80 | 66.30 | 67.90 | 70.80 | 70.00 | 69.90 |
| | Min | 36.80 | 34.20 | 35.90 | 40.40 | 36.50 | 35.90 |
| | Mean ± *SD* | 54.22 ± 8.00 | 54.29 ± 7.56 | 55.02 ± 8.33 | 56.57 ± 8.42 | 57.72 ± 8.26 | 57.02 ± 8.33 |
| $T_a$ (°C) | Max | 38.80 | 39.80 | 39.40 | 38.00 | 38.80 | 38.90 |
| | Min | 27.00 | 26.90 | 27.90 | 26.80 | 26.50 | 27.30 |
| | Mean ± *SD* | 33.11 ± 3.25 | 33.25 ± 3.41 | 33.36 ± 3.12 | 32.92 ± 3.30 | 32.57 ± 3.46 | 32.80 ± 3.26 |
| $V_a$ (m/s) | Max | 2.25 | 2.37 | 2.36 | 0.90 | 1.05 | 0.87 |
| | Min | 0.13 | 0.19 | 0.20 | 0.04 | 0.02 | 0.03 |
| | Mean ± *SD* | 0.81 ± 0.35 | 0.82 ± 0.34 | 0.84 ± 0.37 | 0.24 ± 0.12 | 0.26 ± 0.16 | 0.24 ± 0.12 |
| *G* (W/m$^2$) | Max | 874.00 | 841.00 | 878.00 | 531.00 | 578.00 | 569.00 |
| | Min | 104.00 | 106.00 | 112.00 | 24.00 | 32.00 | 32.00 |
| | Mean ± *SD* | 468.37 ± 217.43 | 462.02 ± 202.48 | 493.91 ± 219.50 | 76.09 ± 58.42 | 75.50 ± 59.82 | 82.78 ± 61.00 |

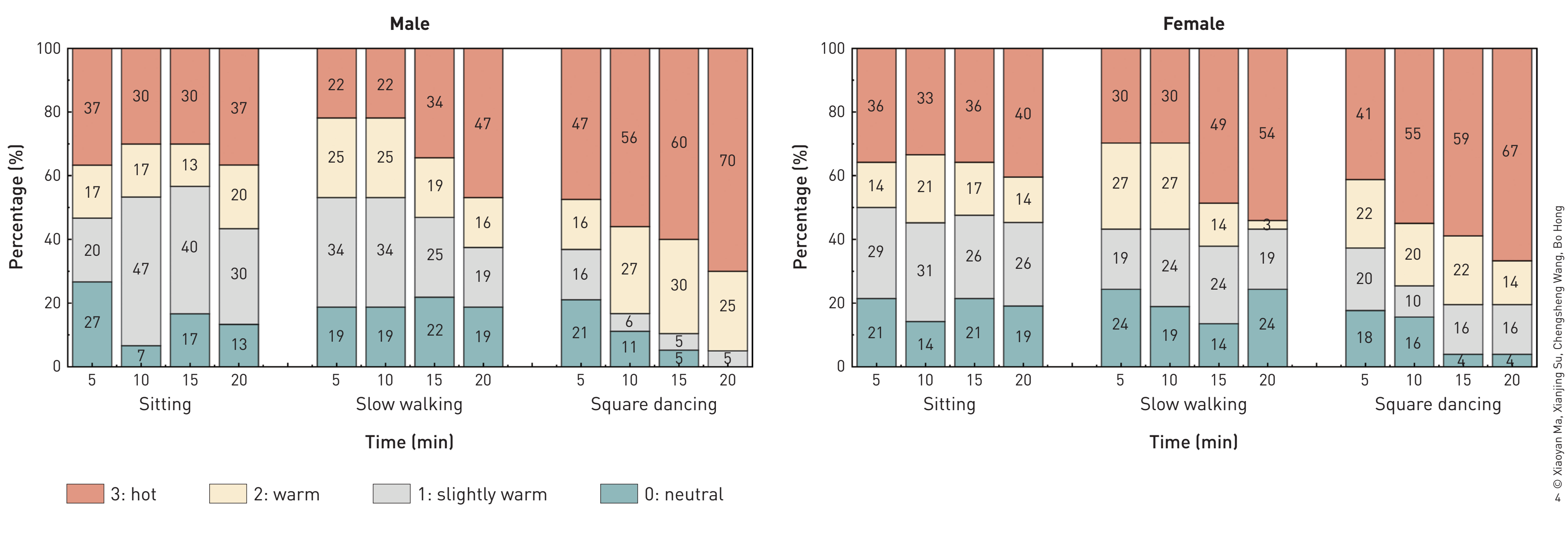



**Fig. 4** Percentage distribution of TSV responses.

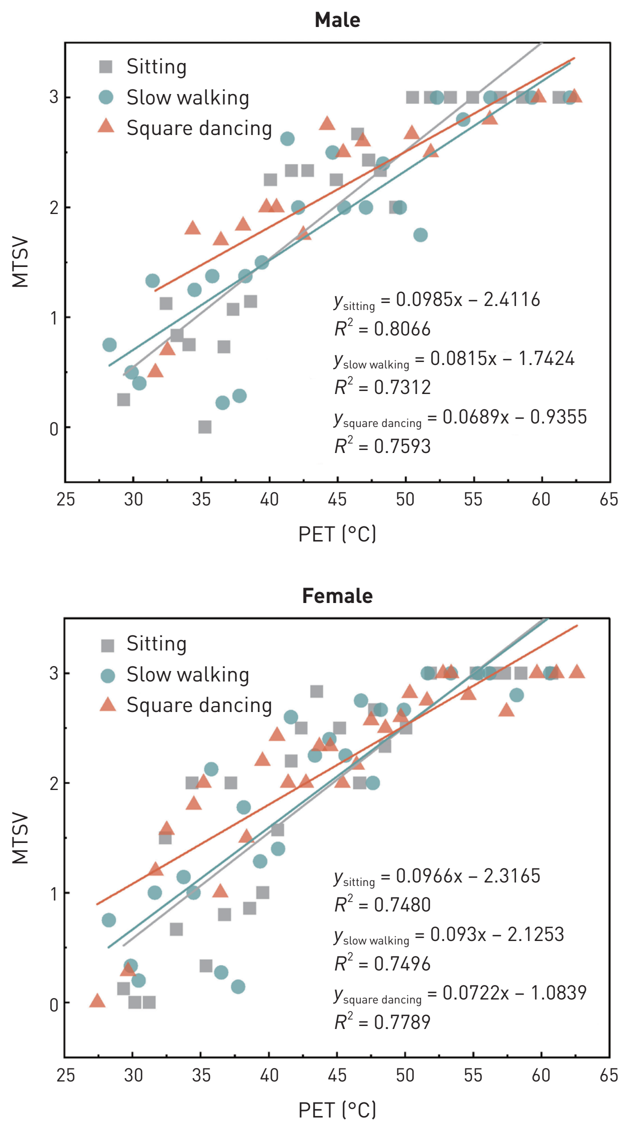





**Fig. 5** Correlation relationship between PET and MTSV.

### 3.4 Physiological Responses

#### 3.4.1 Heart Rate

In older men, mean *HR* showed minimal variation during 20 min of sitting, ranging from 73.07 bpm to 75.67 bpm. After 5 min of slow walking, the *HR* rose sharply from 73.45 bpm to 83.34 bpm, further increased to 87.34 bpm after 15 min, and then stabilized. During square dancing, *HR* consistently climbed, with the most significant rise occurring in the first 5 min (77.57 ~ 93.8 bpm), eventually peaking at 101.88 bpm after 20 min.

Older women exhibited higher mean *HR* values across all activity types compared to men. While sitting, their *HR* ranged from 81.38 to 81.74 bpm. After 5 min of slow walking, *HR* rose from 81.25 bpm to 93.02 bpm, followed by slight fluctuations. In square dancing, the most notable change occurred in the first 5 min (80.85 ~ 100.27 bpm) and continued to rise, reaching a maximum of 109.21 bpm after 20 min (Fig. 6).

#### 3.4.2 Core Temperature

In older men, mean $T_c$ showed little variation during 20 min of sitting, ranging from 36.93°C to 37.02°C. During slow walking, $T_c$ exhibited a U-shaped pattern, reaching a minimum of 36.84°C at 10 min. During square dancing, $T_c$ gradually increased in the first 10 min and rose more noticeably after 15 min, from 36.95°C to 37.09°C, before stabilizing.

Older women demonstrated similar stability in mean $T_c$ during 20 min of sitting. During slow walking, $T_c$ decreased slightly at 10 min and then gradually increased. In contrast to men, $T_c$ in women consistently increased throughout the 20 min of square dancing, rising from 36.90°C to 37.09°C (Fig. 7).

#### 3.4.3 Skin Temperature

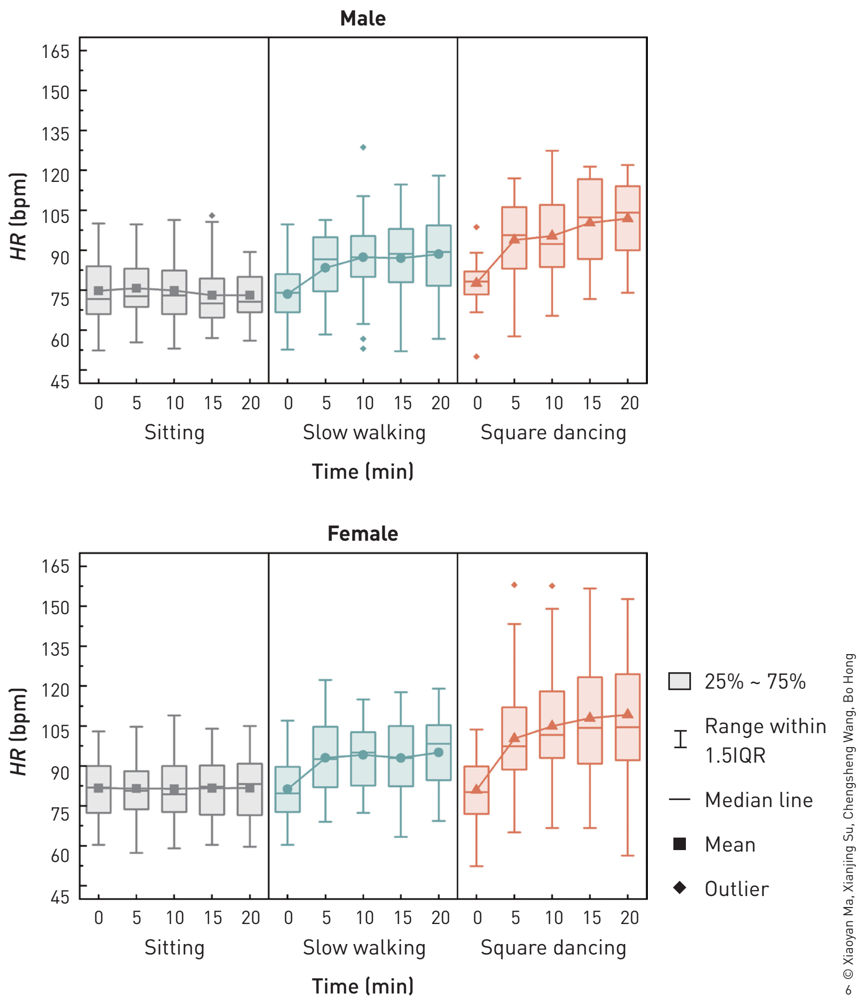
In older males, the mean $ST_{thigh}$ gradually rose from 35.23°C to 35.61°C during 10 min of sitting before stabilizing. Conversely, $ST_{thigh}$ rapidly declined from 35.46°C to 34.92°C within the initial 10 min of slow walking, stabilized at 34.85°C by 20 min. During square dancing, $ST_{thigh}$ followed the same trend as slow walking but remained consistently higher values. Older females showed similar $ST_{thigh}$ patterns across all activities, with minimal variation during sitting and an initial decline followed by stabilization during slow walking and square dancing.

In older males, the mean $ST_{forehead}$ during sitting fluctuated between 35.68°C and 35.88°C. After 5 min of slow walking, $ST_{forehead}$ exhibited a moderate decline from 35.59°C to 35.34°C. During square dancing, it demonstrated a pronounced ascending from 35.35°C to 35.78°C. Older females displayed identical $ST_{forehead}$ patterns to males during sitting and slow walking, whereas square dancing induced rapid elevation within the initial 10 min and then stabilized, differing from the male responses.

In older males, the mean $ST_{back}$ increased from 34.41°C to 34.80°C while sitting. The $ST_{back}$ during slow walking and square dancing displayed a U-shaped trend, rapidly decreased within the initial 10 min and then gradually increasing. In older women, $ST_{back}$ values were consistently higher than those in males across all activities and remained stable during walking and dancing, showing a significant gender-related difference.

For both older males and females, the mean $ST_{chest}$ remained stable across different activities, showing minimal variation with changes in duration or intensity. This stability likely reflects the proximity of the chest to the body's core, where thermoregulatory mechanisms act to maintain a relative stable $T_c$.

In older men, the mean $ST_{upper\ arm}$ gradually increased from 34.42°C to 34.76°C during sitting and slowly declined during slow



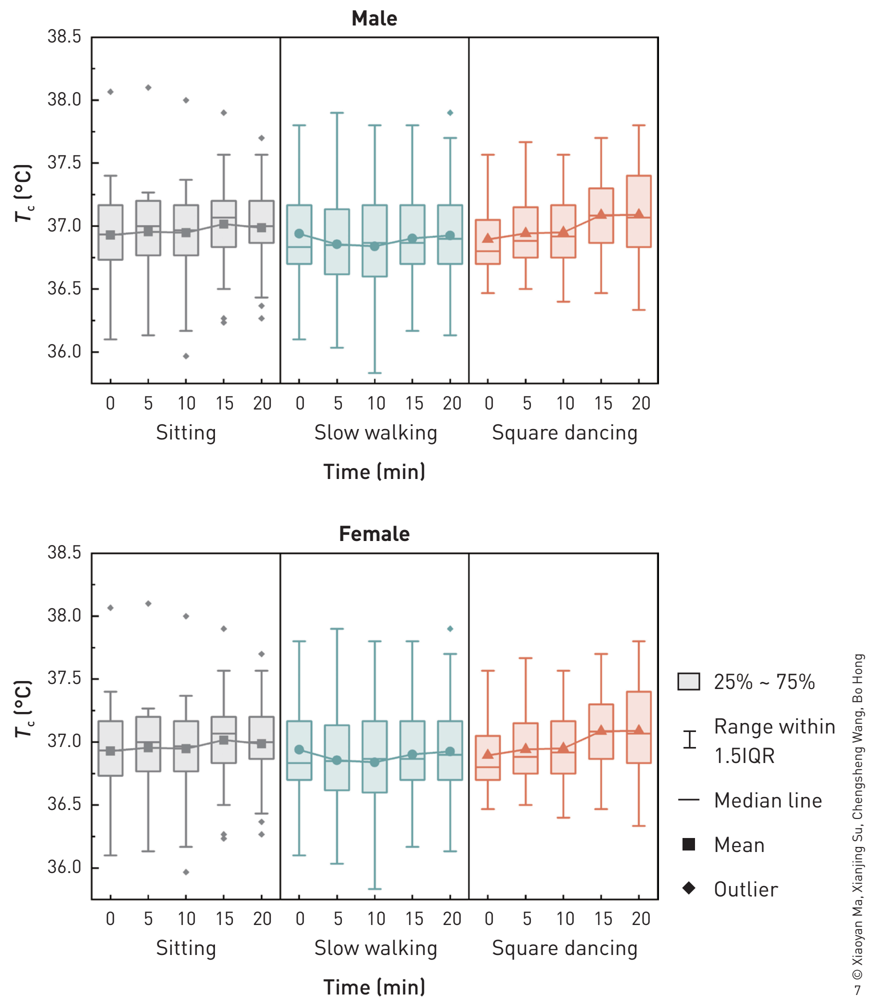




**Fig. 6** Changes in *HR* over time in older males and females.
**Fig. 7** Changes in $T_c$ over time in older males and females.

walking. During square dancing, the $ST_{upper\ arm}$ decreased at the initial 10 min and then stabilized. Older women displayed similar patterns in $ST_{upper\ arm}$ changes but had overall higher $ST_{upper\ arm}$ values compared with men (Fig. 8).

## 3.5 Gender-Specific Thermal Comfort Prediction Model

### 3.5.1 Input Feature Selection

#### 3.5.1.1 Spearman Correlation Analysis

In older males during sitting, the strongest significant correlations with TSV ($p < 0.01$) were observed for $ST_{thigh}$, $ST_{forehead}$, $ST_{back}$, and $ST_{upper\ arm}$, while *HR* exhibited no significance. During walking, $ST_{thigh}$ ($r = 0.532$) and $ST_{upper\ arm}$ ($r = 0.425$) exhibited the highest correlation with TSV among skin temperatures, concurrent with a strengthened *HR*–TSV correlation. During dancing, $T_c$ showed the strongest association with TSV, while *ST*–TSV associations were weaker.

In older females, during sitting, significant correlations with TSV were observed for *HR*, $T_c$, $ST_{thigh}$, and $ST_{upper\ arm}$. Walking activity was associated with stronger *ST*–TSV correlations, with the three highest coefficients observed at $ST_{thigh}$, $ST_{upper\ arm}$, and $ST_{forehead}$. During dancing, TSV showed stronger correlations with core-proximal indices, i.e., $T_c$ and $ST_{chest}$, whereas correlations with peripheral *ST* were weaker (Fig. 9).

#### 3.5.1.2 Feature Importance Evaluation

For older men during sitting, *ST*-related variables demonstrated primary importance, with $ST_{mean}$, $ST_{thigh}$, $ST_{upper\ arm}$, $ST_{forehead}$, and $ST_{back}$ as key predictors while *HR* and $T_c$ showed minimal relevance. During slow walking, *ST* dominance was maintained ($ST_{thigh} = 0.99$, $ST_{upper\ arm} = 0.69$, $ST_{forehead} = 0.58$), consistent with the correlation analyses. During square dancing, the importance of *ST*-related variables diminished, and *HR*

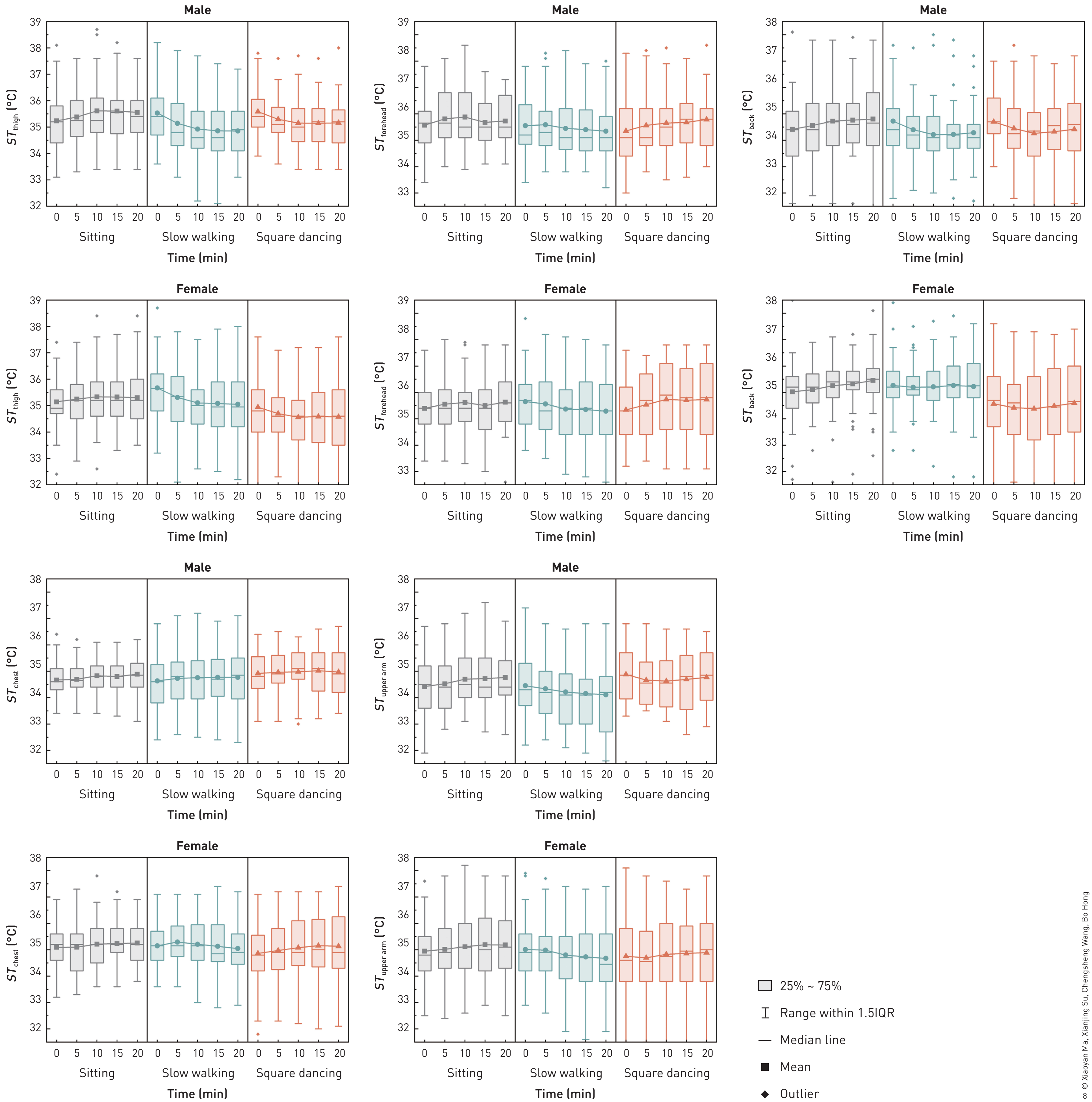



**Fig. 8** Changes of five-spot *ST* over time in older males and females.

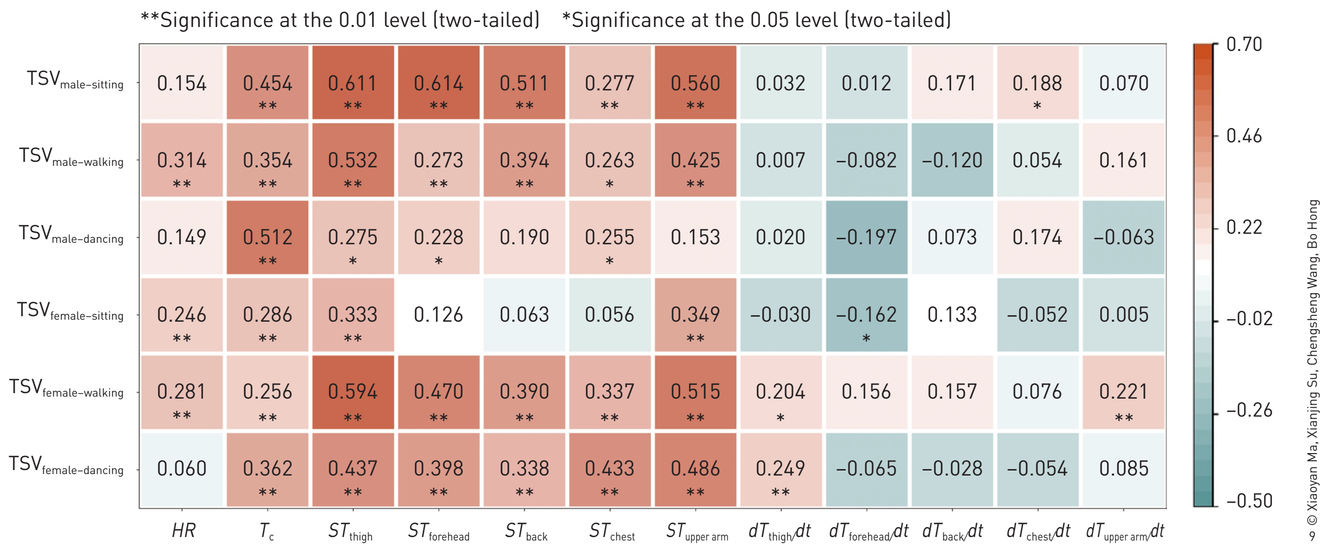



**Fig. 9** Spearman correlation analysis between physiological variables and TSV.
**Fig. 10** Feature importance evaluation results.

emerged as the strongest predictor (0.77).

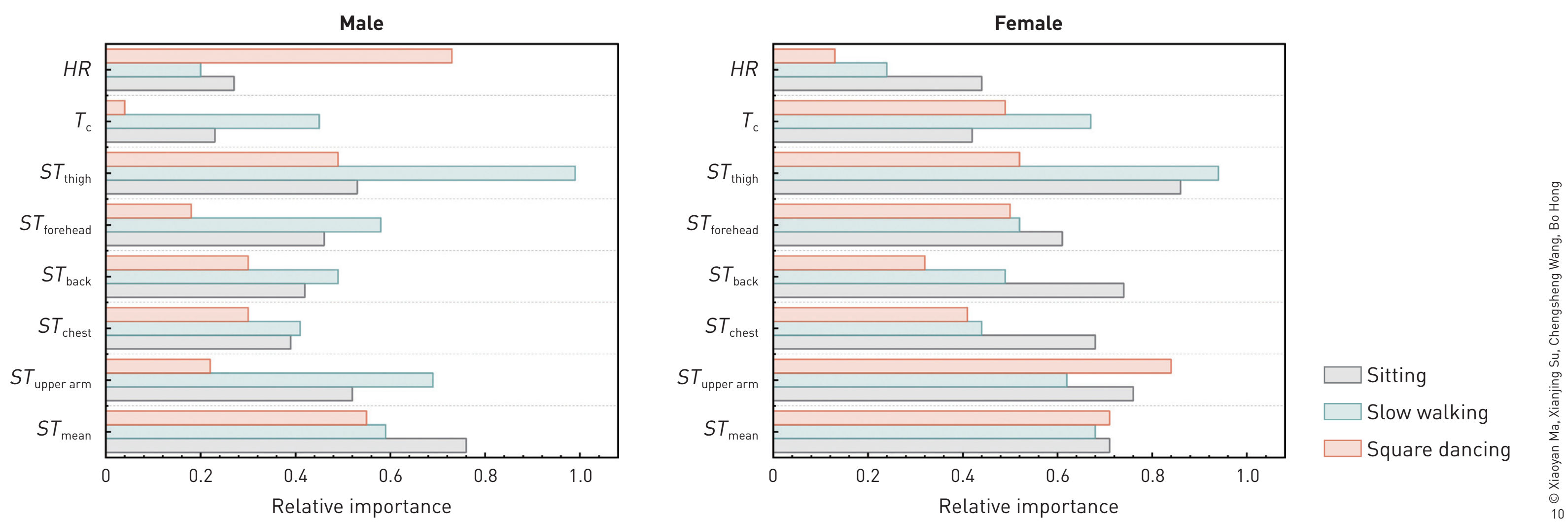
For older females, all the variables exhibited higher overall feature importance for TSV than for males. During sitting, $ST_{thigh}$ (0.86) and $ST_{upper\ arm}$ (0.76) demonstrated the highest importance, surpassing both $HR$ and $T_c$. During slow walking, $ST$-related variables ($ST_{thigh}$, $ST_{upper\ arm}$, $ST_{forehead}$) maintained important, with the importance of $T_c$ increased. During square dancing, $ST_{upper\ arm}$ (0.84) emerged as the strongest predictor (Fig. 10).

Both methods indicated strong correlations of $ST$, $HR$, and $T_c$ with TSV across activities for older adults. These variables were therefore selected to develop gender-specific TSV prediction models. The key predictors were identified as follows. For older men, the key predictors during sitting were $ST_{thigh}$, $ST_{upper\ arm}$, $ST_{forehead}$, and $ST_{back}$; during slow walking, they were $HR$, $ST_{thigh}$, $ST_{upper\ arm}$, and $ST_{forehead}$; and during square dancing, they were $HR$, $T_c$, $ST_{thigh}$, and $ST_{chest}$. For older women, the key predictors during sitting were $HR$, $ST_{thigh}$, $ST_{back}$, and $ST_{upper\ arm}$; during slow walking, they were $HR$, $ST_{thigh}$, $ST_{forehead}$, and $ST_{upper\ arm}$; and during square dancing, they were $ST_{thigh}$, $ST_{forehead}$, $ST_{chest}$, and $ST_{upper\ arm}$.

For each combination of gender and activity, multiple candidate models were systematically developed by evaluating all possible combinations of the identified key predictors. Their performance was compared based on prediction accuracy, $MSE$, and $R^2$ to select the final predictive model.

### 3.5.2 Model Development and Validation

The TSV prediction accuracy in older males and females is displayed in Fig. 11. For older males in the sitting condition, the L12 model (predictors: $ST_{thigh}$, $ST_{upper\ arm}$, and $ST_{forehead}$) demonstrated the best overall performance, with a prediction accuracy of 0.776,



an $MSE$ of 0.217, and an $R^2$ of 0.790. During slow walking, the M8 model, using $ST_{thigh}$ and $ST_{forehead}$ as predictors, attained peak performance with an accuracy of 0.855, an $MSE$ of 0.145, and an $R^2$ of 0.876. During square dancing, the V10 model, using $ST_{thigh}$ and $ST_{chest}$ as predictors, demonstrated optimal performance, achieving 0.874 prediction accuracy with the lowest $MSE$ (0.106) and highest $R^2$ (0.836). These results confirm that the temperature of these cutaneous regions possess strong explanatory power for TSV.

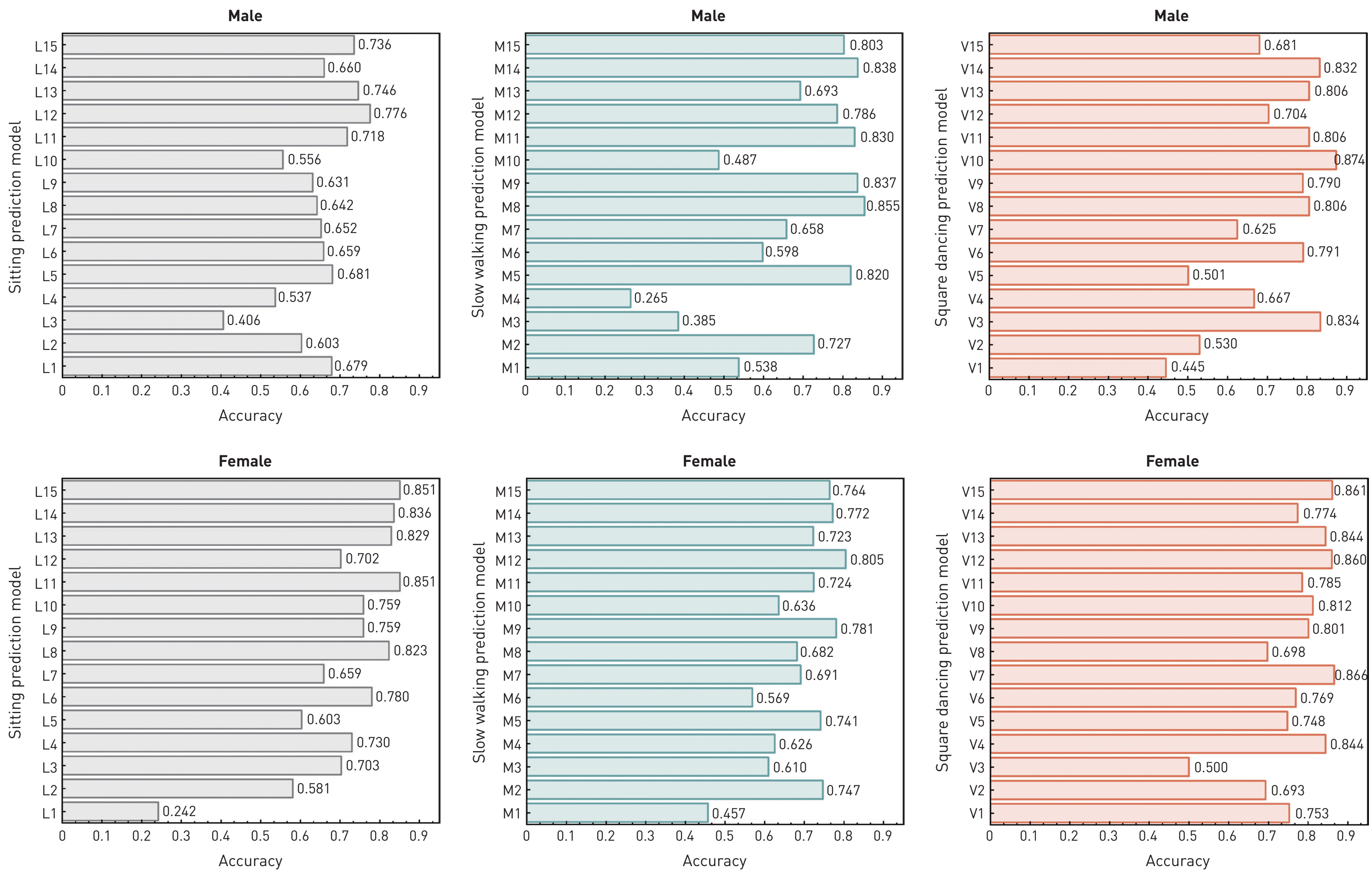
For older women, in the sitting condition, both the L11 model (predictors of $HR$, $ST_{thigh}$, and $ST_{back}$) and the L15 (predictors of $HR$, $ST_{thigh}$, $ST_{back}$, and $ST_{upper\ arm}$) exhibited equivalent accuracy (0.851). Based on the principle of parameter parsimony, L11—with an $MSE$ of 0.142 and an $R^2$ of 0.891—was selected as the optimal model. In terms of slow walking, M12 using $HR$, $ST_{thigh}$, and $ST_{upper\ arm}$ as predictors attained optimal TSV prediction performance, demonstrating minimal $MSE$ (0.163), maximal $R^2$ (0.868), and high accuracy (0.855). For square dancing, all models performed robustly, with V7 (predictors: $ST_{thigh}$ and $ST_{upper\ arm}$) achieving peak performance—an accuracy of 0.8657, an $MSE$ of 0.1160, and an $R^2$ of 0.8935 (Fig. 11, details see supplementary material).

# 4 Discussion

## 4.1 Gender-Specific Thermal Perception

Age-related declines in sudomotor function and cutaneous vasodilation progressively blunt thermal sensitivity as exercise intensity rises[26]. Sex-specific responses further modulate this

**Fig. 11** TSV prediction accuracy in older males and females.



process: at rest, males' higher basal metabolic rate yields marginally greater thermal sensitivity[27], whereas during walking and dancing, their larger muscle mass accelerates endogenous heat production, thereby attenuating thermal sensitivity relative to females[28]. Consequently, older males may perceive ambient thermal changes later and initiate behavioral thermoregulation more slowly under high metabolic loads, potentially increasing heat-stroke risk compared with females.

Older women sustained *HR* that were 10% ~ 15% higher throughout the activities, compensating for a 20% ~ 25% smaller cardiac volume and lower stroke volume[29]. $T_c$ displayed divergent patterns between genders during the same activities. During slow walking, males typically showed a U-shaped curve, characterized by initial vasoconstriction followed by a sweat-mediated rebound[30]. In contrast, females exhibited minimal fluctuation during this activity, yet their $T_c$ remained significantly elevated compared to males. During square dancing, both genders showed a sustained increase in $T_c$. However, the temporal patterns differed markedly: male $T_c$ tended to plateau after approximately 15 min of activity, whereas female $T_c$ continued to rise throughout the entire 20 min period, demonstrating a consistently steeper climb. This pronounced and prolonged rise in females may be attributed to factors such as a lower surface-to-mass ratio, thicker subcutaneous insulation, and estrogen-enhanced vasoconstrictor tone, which elevates the heat-dissipation set-point [31]. Thus, morphometric and neuroendocrine constraints may delay heat loss in women, while age-related attenuation of vasodilation still predisposes men to rapid $T_c$ surges under high metabolic loads[32]. These morphological and neuroendocrine mechanisms can be used to explain the phenomenon of "delayed heat dissipation" observed in older women.

The observed gender differences in correlations between thermal sensation and physiological indicators across activity levels can be systematically interpreted in terms of the dynamic thermoregulation responses and gender-related physiological mechanisms. As activity intensity increased from sitting to slow walking to square dancing, older men showed a shift from a peripheral-dominant to a core-dominant regulation pattern[8]. During sitting and slow walking, $ST_{\text{thigh}}$ and $ST_{\text{forehead}}$ were strongly correlated with TSV, suggesting that under low thermal load, heat dissipation mainly depends on peripheral vasomotor adjustments[10]. The weaker link with *HR* indicates that the cardiovascular responses have not yet become the primary cooling pathway. At higher intensity (e.g., square dancing), metabolic heat production rose sharply, shifting regulation toward preventing the core from overheating. $T_c$ then replaced *ST* as the main driver of TSV, reflecting a physiological strategy that prioritizes core stability under high thermal stress[8]. In contrast, older women showed significant correlations between TSV, *HR*, and $T_c$ even at rest. This may stem from their higher body fat percentage and lower muscle mass, which reduce resting metabolic heat production and require earlier cardiovascular and core thermoregulatory responses to maintain thermal balance[32]. During slow walking, *ST* became more strongly correlated with TSV, indicating a greater reliance on precise peripheral blood flow control at moderate intensity. At higher intensity, TSV correlated closely with both $T_c$ and $ST_{\text{chest}}$, reflecting a focus on maintaining trunk heat dissipation. This suggests that women may employ a more conservative thermoregulatory strategy under heat stress, emphasizing efficient core cooling to preserve homeostasis[31].

The proposed TSV models for older park users require only *HR* and two to three local *ST* inputs, while achieving improved parsimony and accuracy compared with previous approaches. Unlike Jiangnan Wang et al., who applied Standard Effective Temperature (SET*) calibrated on young adults to frail elders[33], the regressors in this research are derived from gender-specific geriatric data. Compared with the comprehensive Chinese-elder thermoregulation model[34] proposed by Ting Ma et al., which demands more than 12 parameters and impedes real-time use, this study's framework remains tractable. Furthermore, the indoor–outdoor adaptation relations proposed by Wuxing Zheng et al. and Yu Jiao et al. ignore physiological predictors such as *ST*[35–36], whereas the current models explicitly incorporate them, yielding markedly higher predictive power.

### 4.2 Design Implications

Based on the observed gender-specific thermal patterns, this study proposes an activity-zoned, climate-responsive park framework. The layout follows activity-based zoning principles. High-intensity areas (e.g., squares, fitness zones) should primarily address the cooling needs of older men. These spaces should incorporate shading from broad-canopy trees suitable for Xi'an's climate (e.g., *Platanus orientalis*, *Styphnolobium japonicum*) and employ light-colored granite or high-albedo permeable concrete pavement to minimize surface heat gain[22]. Spatial organization should promote natural ventilation and may be supplemented by low-speed misting systems, responding to men's lower NPET (13.58°C) during square dancing.

Medium- and low-intensity zones (e.g., seating areas, walking paths) should prioritize thermal comfort for older women. Reflecting their heightened sensitivity to solar radiation, as shown by the strong association between $ST_{\text{upper arm}}$ and TSV, seating areas should incorporate hybrid shading strategies combining dense-foliage trees (e.g., *Aesculus chinensis*, *Ginkgo biloba*) with pergolas. Walking paths require continuous canopy cover from species such as *Fraxinus chinensis* and *Koelreuteria paniculata*, aligned with women's higher NPET during walking (22.85°C). Resting facilities should utilize materials with low thermal capacity and high reflectivity (e.g., wood, light-toned metals) to minimize surface heat retention, which is particularly relevant for older women with reduced heat dissipation capacity[37].

Beyond physical design interventions, dynamic thermal protection may be embedded via smart technology. A real-time heat–health warning system integrated with wearable devices could be developed. To overcome the practical limits of multi-site *ST* inputs, a simplified model should be calibrated that conveniently maps wrist temperature and *HR* to the equivalent temperatures at the key anatomical sites required by the predictors. When the predicted thermal sensation nears safety thresholds, issue alerts via a mobile app or a park broadcast to encourage people to adjust their activities or move to cooler areas. This simplifies complex physiological monitoring by converting it to wearable measurements, enabling a shift from static design to dynamic intervention and providing a clear pathway to precise, proactive, age-friendly park management.

### 4.3 Limitations and Future Direction

This study has several limitations. First, it was conducted in a single urban park in Xi'an. Future research should apply the same approach across different climatic regions and urban settings to improve the generalizability of the findings. Second, the sample included only healthy adults aged 60 ~ 84 years, excluding individuals with chronic diseases (e.g., cardiovascular, diabetic, or respiratory conditions) and the very old population (more than 84 years). These populations may have distinct thermoregulatory and comfort responses. Future studies should therefore include a broader range of ages and health conditions to strengthen the conclusions. Finally, additional individual factors, e.g., age, body mass index, and clothing insulation, should be further examined for their potential effects on thermal comfort in older populations.

## 5 Conclusions

By integrating synchronous micrometeorological data, physiological signatures, and structured questionnaires collected during sitting, slow walking, and square dancing in an urban park in Xi'an, we quantified gender-specific thermal perception and derived gender-differentiated TSV models. The principal findings were as follows.

1) Sitting older females showed lower NPET (23.98°C) but wider range of NPETR (18.80 ~ 29.16°C) than older males. Conversely, during slow walking and square dancing, these women exhibited higher NPET (22.85°C, 15.01°C) and narrower range of NPETR (17.48 ~ 28.23°C, 8.09 ~21.94°C) than men.

2) Older females had higher *HR* than males across all activities, especially during square dancing. Older men showed U-shaped $T_c$ changes during slow walking (minimum: 36.84°C), while older women exhibited progressively rising $T_c$ during square dancing (peak: 37.09°C). Limb *ST* (e.g., thigh, upper arm) varied more with activity intensity, whereas trunk *ST* (chest) remained stable.

3) During sitting, older men showed significant *ST*–TSV correlations ($p < 0.01$). Walking strengthened *HR*–TSV associations, while square dancing was characterized by $T_c$-dominated TSV responses with attenuated *ST* associations. In older women, TSV strongly correlated with $ST_{\text{upper arm}}$ during sitting. Walking enhanced their *ST* associations, whereas square dancing highlighted proximal factors alongside declining distal *ST* correlations.

4) For older men, optimal TSV predictors during sitting, walking, and square dancing were combinations of $ST_{\text{thigh}}$, $ST_{\text{upper arm}}$, and $ST_{\text{forehead}}$; $ST_{\text{thigh}}$ and $ST_{\text{forehead}}$; and $ST_{\text{thigh}}$ and $ST_{\text{chest}}$, respectively. For older women, the best predictive combinations during sitting, slow walking, and square dancing were *HR*, $ST_{\text{thigh}}$, and $ST_{\text{back}}$; *HR*, $ST_{\text{thigh}}$, and $ST_{\text{upper arm}}$; and $ST_{\text{thigh}}$ and $ST_{\text{upper arm}}$, respectively.

## ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at https://doi.org/10.15302/J-LAF-2026-0011.

**Competing interests** | The authors declare that they have no competing interests.

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# 夏季室外不同活动强度下老年人热生理响应的性别差异：一项基于中国寒冷地区的实地研究

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**摘要**

全球老龄化与极端高温频发加剧了老年人户外热安全风险。本研究于西安某城市公园开展实验，同步采集老年使用者在静坐、散步及广场舞活动状态下的微气候、生理与热感觉数据。基于统计分析与机器学习方法筛选预测因子，构建了性别差异化的梯度提升决策树热感觉预测模型。结果表明：1）中性生理等效温度（NPET）随活动类型发生了显著变化。静坐时，女性老年人的NPET低于男性；而在慢走与广场舞活动中，女性的NPET高于男性。2）女性老年人心率（*HR*）在所有活动中始终高于男性，男性老年人核心温度（$T_c$）在散步时呈“U”型变化趋势，肢体皮肤温度（*ST*）随活动强度的增加波动加剧，而前胸*ST*保持稳定。3）热感觉投票（TSV）预测因子具有性别与活动特异性，男性老年人在静坐时TSV主要受*ST*影响，散步时*HR*关联上升，广场舞时以$T_c$为主导。女性老年人TSV在静坐时与上臂*ST*强相关，在广场舞时则主要受$T_c$及前胸*ST*的综合影响。4）本研究构建的性别化TSV预测模型仅需2～3项局部生理参数输入，在预测精度与可操作性上均优于传统热指数。研究结果可直接指导适老化公园设计、提升老年人户外活动安全，并为可持续城市发展提供支撑。

**关键词**

城市开放空间；室外热舒适；老年人群；预测模型；热生理特征

**文章亮点**

- 性别化TSV预测模型在预测精度与可操作性上均优于传统热指数
- 男性老年人TSV分别与*ST*（静坐）、*HR*（散步）及$T_c$（广场舞）显著相关
- 女性老年人TSV在静坐时与上臂*ST*具有相关性，广场舞时则与$T_c$和前胸*ST*相关
- 男性老年人TSV最优预测组合为大腿*ST*及其他部位*ST*，女性老年人则为*HR*、大腿*ST*和其他部位*ST*

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