The effectiveness of e-textiles in providing thermal comfort: a systematic review and meta-analysis

Abstract

Thermal electronic textiles (e-textiles) are increasingly common in the market and aim to provide thermal comfort in cold environments. Currently, however, there is a paucity of information on the relative effectiveness of the different types of thermal e-textile. This study sets out to compare the effectiveness of a range of such textiles reported in the relevant literature. The study addresses the issue of heating effectiveness in terms of gender and particular body regions. Among the results reported, three primary categories emerged for investigation: (1) metabolic response, comprising metabolic rate (MR) and heart rate (HR); (2) respiratory response i.e. mean skin temperature ($\overline{T}_{sk}$); and (3) perceptual response, including thermal sensation (TS) and comfort sensation (CS). Eight eligible studies with a total of 83 subjects aged 23.4±1.49 yr., 40.96% male and 37.35% female and 21.69% in which gender was not reported were investigated for the meta-analysis. Results show a significant improvement in $\Delta\overline{T}_{sk}$ and ΔTS between the control (CON) and experimental (HEAT) groups via heating intervention ($p<0.05$), but results were not significant for ΔMR, ΔHR and ΔCS ($p>0.05$). Regarding gender, thermal e-textiles significantly enhanced the $\Delta\overline{T}_{sk}$ in males and ΔTS in both males and females ($p<0.05$). With regard to different body regions being heated, there were significant effects on $\Delta\overline{T}_{sk}$, ΔTS and ΔCS in heating the upper torso ($p<0.05$) and on ΔTS in heating the feet and toes ($p<0.05$). The results reported here may serve as reference points for the further development of smart heating textile technology.

Keywords

heating textile, body region, perceptual response, thermal comfort, meta-analysis, systematic review

Introduction

In recent years, applications of heating electronic textiles have expanded from purely personal protection to healthcare and medical usage.[1,2] In academic studies, prototypes discussed include a variety of clothing,[3–5] wearables[6,7] and sleeping bags,[8–10] which aim at improving blood circulation to achieve thermal comfort during daily activities in cold environments, and improving sleep quality. Some of these textiles were developed to provide a foot-heating system to treat certain foot conditions.[11] In some applications temperature can be adjusted automatically with wireless charging, which facilitates remote usage.[7] The results of studies illustrate the effectiveness of each textile product in ameliorating human thermal comfort in different situations. In terms of systematic review and meta-analysis, a number of studies have examined personal comfort systems (PCSs)[12] and the effectiveness of cooling garments in minimizing heat strain.[13] Such studies compare the effects of heating/cooling on the body with reference to users' perceptual responses. However, there is an overall lack of studies investigating the effectiveness of heating products in achieving thermal comfort generally. In fact, it would be helpful to focus on investigating the efficacy of thermal comfort in specific body regions. Also, currently, there is no standardized way to compare study results statistically. Therefore, using meta-analysis provides advantage in summarizing the effectiveness in enhancing the human thermal comfort regardless of the various form of heating textile products. Although there might be certain publication bias and limited data in the process of meta-analysis, it is still an objective and comprehensive method to analyze a pooled data with highly accuracy of the results. Thus, this systematic review and meta-analysis seeks to address these issues and to flag possible pathways for future research.

Table 1. List of abbreviations used in this article.

Abbreviation	Explanation
AI	Artificial Intelligence
CI	Confidence Intervals
CON	Control Group
CS	Comfort Sensation
HCP	Heating Clothes/Pads
HEAT	Experimental Group

HR	Heart Rate
HSB	Heating Sleeping Bag/Socks/ Insoles
HV	Heating Vest
MR	Metabolic Rate
PCSs	Personal Comfort Systems
PICO	Participants, Intervention, Comparison And Outcome
PRISMA	Preferred Reporting Items For Systematic Reviews And Meta-Analyses
RCT	Randomized Control Trial
SMDs	Standardized Mean Differences
$\bar{\mathbf{T}}_{\mathbf{local}}$	Mean Local Temperature
$\bar{\mathbf{T}}_{sk}$	Mean Skin Temperature
TS	Thermal Sensation

Research questions

The research sets out to address three questions: (1) Are heating e-textiles effective in improving human thermal comfort? (2) Which body regions reveal the most satisfactory thermal comfort when heated by an e-textile? (3) Do heating effects vary according to gender?

Objectives

This research has three objectives: (1) To determine the effects of various types of heating e-textiles on human thermal comfort. (2) To identify the body regions with the most significant improvement in thermal comfort. (3) To compare the effects of a variety of thermal e-textiles on thermo-regulatory body region responses and the perceptual responses made by male and female subjects.

Research design

A preliminary review of the literature has been carried out into trials seeking to evaluate the efficacy of heating e-textiles in cold environments.[4–10,14–18] Relevant keywords related to heating, textile and cold environments were identified and preliminary results showed that the common body regions heated by thermal e-textiles are: (1) torso, (2) feet/toes and (3) more than two regions. To examine thermal wear performance, researchers generally had an experimental group (HEAT) placed in a cold environment and a control group (CON) situated in a thermo-neutral or in a cold environment but wearing unheated clothing. The environment was a climate chamber with adjustable settings for ambient temperature, relative humidity and air velocity. In the present study, the cold exposure and the presence of heat source were the independent variables. Participants were usually running, walking, standing or sitting during the testing, and results are expressed quantitatively in terms of various parameters, such as whole body and local thermal sensation, to compare the effects of the intervention of heating e-textiles. However, these parameters were not standardized to compare the performance of a diverse range of heating e-textiles in different environmental conditions. Therefore, a means of comparing the effectiveness of different prototypes was applied to quantify the differences in the cold environment.[19] The outcome (the dependent variable) may be expressed as mean skin temperature ($\overline{T}_{sk}$), thermal sensation (TS) and comfort sensation (CS). TS expresses the thermal experience of different individual human body parts under a variety of environmental conditions, while CS refers to the human satisfaction towards various thermal conditions with subjective perception.[20] Usually, a temperature sensor would be attached at the specific local body part to record $\overline{T}_{sk}$. In terms of TS and CS, the subjective evaluation would be often assessed by perception ratings from the responders.[4,7–10,15,16]

Age group, gender, thermal sensitivity and the type of heating e-textile, i.e., different body region being heated may be considered as moderators. In this study, moderators investigated are restricted to gender and heated body regions. The target age group selected was 20 to 30 years old to minimize the bias in sensitivity variation among children and the elderly. This hypothesizes that the performance of adults in the 20–30 age range reflects general human thermal comfort. Thermal sensitivity varies among adults but few studies have taken this into account, therefore it is not included as a moderator in this research.[4] A conceptual framework of the study is shown in Figure 1.

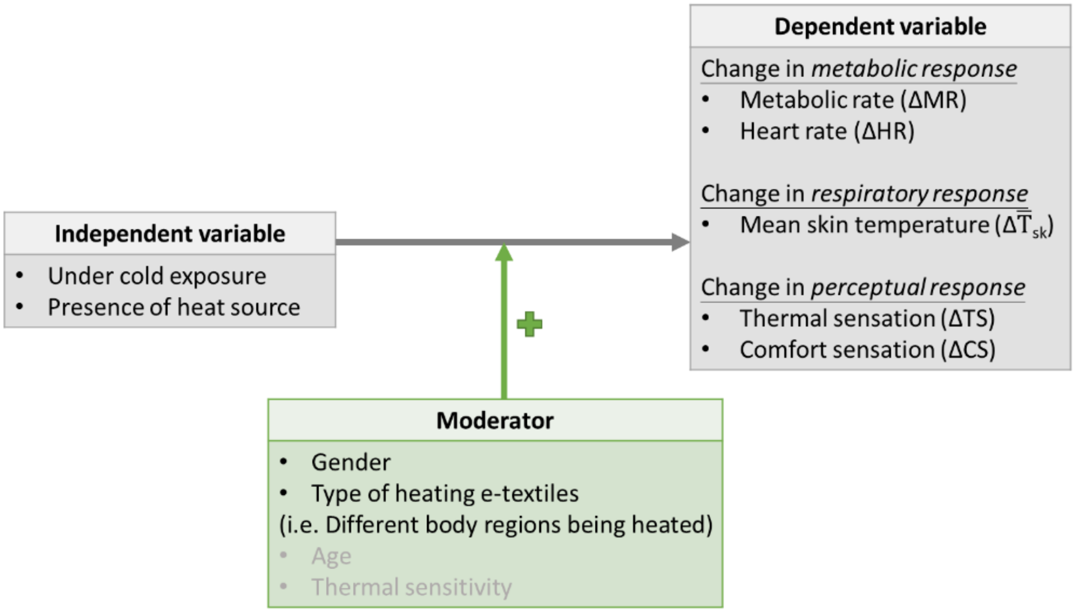


Figure 1. Conceptual Framework.

Method

The systematic review used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)[21] as a checklist for screening the published literature in terms of certain inclusion criteria. This is a four-stage process: identification, screening, qualification and inclusion.

Research procedures and data collection

In the stage of identification, there were total nine databases being recorded and studied. Databases with duplication, non-English publications and without full text would be removed before screening. No special restrictions were placed on the publication dates of the literature. Databases used were Google Scholar (1948–2022), Scopus (1932–2022), Science Direct (1964–2022), Web of Science (1989–2022), Wiley Online Library (2018–2022), Taylor and Francis Online (2008–2020), ProQuest (1986–2018) and Springer (2015–2022). In terms of search strategy, the Boolean conjunctions “AND” and “OR” were applied in keyword searches. Keywords included: “heating” OR “electrically heated” OR “thermal” AND “textile”

OR “clothing” OR “pad” OR “wearable” AND “thermal comfort” OR “health” OR “heating efficiency” OR “cold environment” OR “thermal regulation” OR “smart”.

Eligibility criteria

Eligible data was collected according to the PICO (Participants, Intervention, Comparison and Outcome) approach. Inclusion criteria for the studies included: (1) Participants: studies included healthy participants aged between 20 and 30 years. (2) Interventions: only heating e-textiles used in trial tests in which subjects were running, walking, standing or sitting are included. (3) Environment: tests were conducted in a climate chamber with controllable ambient temperature, relative humidity and air velocity. (4) Comparison groups: HEAT and CON groups figured in the eligible studies. Method: studies using both the blind method and randomized control trial (RCT) were included. (5) Outcome measures: objective measurement in terms of (a) metabolic response, such as heart rate (HR) and metabolic rate (MR), (b) thermo-regulatory response, such as $\overline{T}_{sk}$ and (c) perceptual response in TS (e.g. cold-warm feeling) and CS (e.g. local comfort and overall comfort).

Certain types of study were excluded from this review: (1) Those with duplicate records, partial texts or abstract-only papers and non-English publications. (2) Full text English publications that are not textile or wearable-related and which do not feature thermo-electric or conductive heating materials. (3) Studies that do not focus on human thermal comfort or that do not feature active heating pads/textiles. (4) Manikin tests or non-human trial studies and studies with effects that are impossible to measure.

Data extraction

Two reviewers searched and extracted the relevant literature independently to ensure data quality and accuracy. If there was disagreement, a third reviewer was asked to screen the relevant studies based on the eligibility criteria. Table 2 displays the eligible data was extracted from selected studies for quality assessment, including participant information, intervention characteristics, heated body parts with satisfactory comfort, environmental conditions for both HEAT and CON, protocol and outcomes, i.e., changes in objective and subjective measurements recorded as mean ± standard deviations (SDs) for analysis.

Table 2. Items for data extraction and quality assessment

Items	Data Extraction
Publication information	Title, year and author
Participants	Number and gender Average (with standard deviation) age, height, weight, body surface area and body mass index
Intervention characteristics	Type of heating e-textiles: 1) Heating clothes/pads (HCP) 2) Heating sleeping bag/socks/ insoles (HSB) 3) Heating vest (HV)
Heated body regions with satisfied comfort	Three categories/ subgroups: 1) Feet and toes 2) Feet, buttocks and shoulders 3) Upper torso
Environment condition [˚C, % RH, m/s] (both HEAT and CON)	Ambient temperature Relative humidity Air velocity
Protocols	Running, walking and resting distance Duration / Time
Changes in subjective measurement	Heart rate, metabolic rate and thermo-regulatory response
Changes in objective adjustment	Thermal sensation and comfort sensation

Risk of bias

To address possible selection bias, the following steps were taken: (1) Publication bias: Funnel plots were applied in visualizing the distribution of effect size to check for the presence of publication bias. If the result of Fail-safe N and Begg and Mazumdar rank correlation are insignificant (p>0.05), this supports the findings in the funnel plot and shows that there is no publication bias (a detailed explanation is given in the data analysis section below). (2) English-language bias: It is assumed that most valuable publications are written in English, and so relevant studies written in other languages are omitted. (3) Database bias:

Although there is a limited number of studies in each database, this study searched a number of common science databases to enhance coverage.

Data analysis

Results obtained from data extraction in terms of subjective metabolic and thermo-regulatory measurement as well as objective thermal sensation and comfort sensation are presented to achieve the first two objectives of the systematic review.

Meta-analysis of the available data utilised the software Comprehensive Meta Analysis Version 3.0 (CMA V3). All the extracted studies in the review were available for data analysis and the aim was to address the research questions by (1) estimating the mean effect size from selected studies with similar effect sizes and (2) evaluating the moderator subgroups in terms of thermal comfort. Standardized mean differences (SMDs) with 95% confidence intervals (CI) were calculated to evaluate the effect of e-textiles on improving human thermal comfort by comparing HEAT and CON. The research reveals which type of intervention results in the most significant effect. The results are visualized in a forest plot to determine the effect size of each study. This is done to evaluate body region variations, i.e., (1) feet and toes; (2) feet, buttocks and shoulders; (3) upper torso at a statistical significance of $p<0.05$. If the data are significantly heterogeneous, i.e., $I^2>50\%$, then the random-effect model can be applied to calculate the pooled intervention effect. In contrast, if $I^2<50\%$, the fixed effect model can be applied instead to calculate the intervention effect.

Results

Included studies

An overview of search result is given in Figure 2 in the form of a flow diagram. After pre-screening exclusion of nine databases by removing duplication, non-English and abstract-only publications, there were less than five thousand studies screened that had non-related research aims or lacked measurements of human trials at the stage of quality control. Finally, eight studies met the inclusion criteria and all were RCTs (87.5%),[5,7–10,15,16] except one (12.5%).[4]

The eight relevant studies were conducted from 2016 to 2021 except for one from 2009. The studies investigated the heating performance on the body surface in different areas such as (1) feet and toes;[7–10,16] (2) feet, buttocks and shoulders;[15] (3) upper torso[4,5] by different interventions, i.e., specified e-textiles categorized in HCP,[15] HSB[7–10,16] or HV.[4,5] Changes in HR, MR, $\overline{T}_{local}$, $\overline{T}_{sk}$, TS and CS comparing CON to HEAT were recorded. Excluding two studies in which exact ages were not given, there was a total of 83 subjects aged 23.4 ± 1.49 years and comprised of 40.96% males and 37.35% females and 21.69% gender not reported. Participants in one study underwent testing at 23℃; 50% RH. Most of the studies were undertaken in a climate chamber at ambient temperature 1.77 ± 5.10°C, relative humidity 68.33 ± 17% and air velocity 0.52 ± 0.29 m/s (mean ± SD). The protocols included sleeping (62.5%), sitting-running-sitting (12.5%), standing-arm-activity-standing (12.5%) and walking-standing (12.5%).

In terms of perceptual response, perception ratings were applied in several studies to assess TS and CS, such as a 9-point semantic differential scale in TS, i.e., very cold, cold, cool, slightly cool, neutral, slightly warm, warm, hot, and very hot;[4,7–10,15,16] or a 5-point scale, i.e., warm, slightly warm, neutral, slightly cool and cool.[5] CS was evaluated by a 7-point Likert scale, i.e., very uncomfortable, uncomfortable, a little uncomfortable, neutral, a little comfortable, comfortable and very comfortable;[4,16] 4-point scale, i.e., very uncomfortable, uncomfortable, slightly uncomfortable and neutral/ comfortable.[7–10,15]

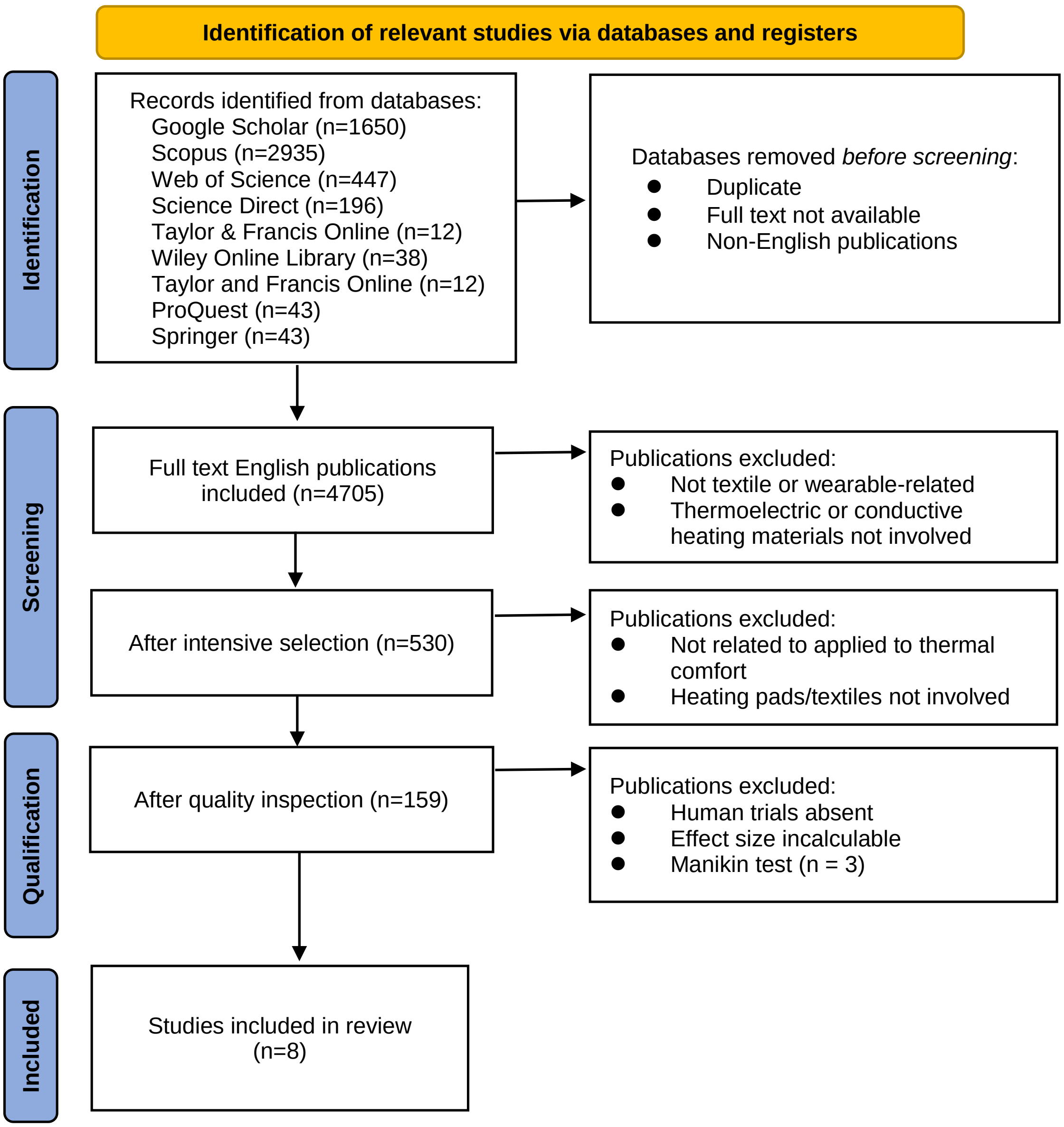


Figure 2. Flow chart for systematic review process of published studies.

Detailed summarized data extraction from these studies included author and participant information, textiles types, effective body region, ambient environment, protocols and changes in outcomes are shown in Table 2 below.

Table 3. A list of data extracted from included studies.

Author (yr)	Participants (n)	Age (yr); height (cm); weight (kg); body surface area (m^2); body mass index (kg/m^2) [mean ± SD]	Textile Types	Effective Body Region	Environment [℃, % RH, m/s]	Protocols	Experimental Targets	Changes in outcomes
Song et al. (2016)	7 males	24.9 ± 1.7 yr.; 172.8 ± 2.6 cm; 62.0 ± 3.5 kg; 1.74 ± 0.06 m^2; 20.8 ± 0.9 kg/m^2	HSB	Feet and toes	−6.4℃; 80% RH; 0.5 m/s	Sleeping 3 hrs	To evaluate the improvement of wearers' local thermal comfort of feet with the intervention of a novel smart heating sleeping bag	↔ MR; ↑ *HR; ↑ **$\overline{T}_{local(feet)}$; ↑ **$\overline{T}_{sk}$; ↑ TS_{feet}; ↑ $TS_{whole\ body}$; ↑ CS_{feet}; ↑ $CS_{whole\ body}$
	7 females	24.0 ± 1.4 yr.; 160.9 ± 2.8 cm; 52.1 ± 4.9 kg; 1.53 ± 0.07 m^2; 20.1 ± 1.6 kg/m^2	HSB	Feet and toes	−0.4℃; 80% RH; 0.5 m/s	Sleeping 3 hrs		↔ MR; ↔ HR; ↑ **$\overline{T}_{local(feet)}$; ↑ **$\overline{T}_{sk}$; ↑ TS_{feet}; ↑ $TS_{whole\ body}$; ↑ CS_{feet}; ↑ $CS_{whole\ body}$
Kim et al. (2021)	18 adults	20s–30s	HV	Upper torso (Abdomen and lower back)	2℃; 60% RH; 1.2 m/s	(Rest 1) sitting 30 min + (running) speed 7.5 km & 3% slope 15 min heating + (Rest 2) sitting 30 min	To examine the tolerable range of skin temperature of abdomen and back waist by monitoring the temperature control of the smart clothing to achieve comfortable thermal sensation	↑ $\overline{T}_{local(abdomen\ and\ lower\ back)}$; ↑ TS (p=0.00); ↑ **CS
Sormunen et al. (2009)	8 males	20s–30s	HV	Upper torso (Chest and lower back)	4℃; 30% RH	Standing with arm activity 1. 10 times (3–4s each) 2. move 5.5kg for 30 min and repeat 4 times with 5 min rest	To study the muscular activity and thermal responses in males and females in repetitive work under a cold exposure	↑ *$\overline{T}_{sk}$; ↑ *TS
	8 females	20s–30s	HV	Upper torso (Chest and lower back)	4℃; 30% RH	Standing with arm activity 1. 10 times (3–4s each) 2. move 5.5kg for 30 min		↑ *$\overline{T}_{sk}$; ↑ *TS

						and repeat 4 times with 5 min rest		
Song et al. (2020)	8 females	24.6 + 1.6 yr.; 160.7 + 5.2 cm; 53.7 + 5.9 kg; 1.6 + 0.1 m^2; 20.8 + 1.4 kg/m^2	HCP	Feet, buttocks and shoulders	5℃; 60% RH; 0.2 m/s	Sleeping 8 hrs	To investigate the effectiveness of partial-body heating in enhancing thermal comfort as well as sleep quality of young female adults in the exposure of cold indoor environment	↔ HR; ↑ *$\overline{T}_{local(feet)}$; ↑ *$\overline{T}_{sk}$; ↑ *TS; ↑ *CS
Chen et al. (2020)	7 males	23.4 + 1.2 yr.; 170.6 + 2.6 cm; 65.3 + 5.4 kg; 1.78 + 0.1 m^2	HSB	Feet and toes	10℃; 65% RH; 0.4 m/s	Twice repeated cycles of 50 min treadmill walking at 4.0 km/h and 20 min standing	To study the effectiveness of the smart wireless charging heating insoles in enhancing the body thermal comfort of young men under an extremely cold environment	↑ *$\overline{T}_{local}$; ↑ *TS_{feet}; ↑ *$TS_{whole\ body}$; ↑ *CS_{feet}; ↑ *$CS_{whole\ body}$
Zhang et al. (2017)	8 females	20.2 + 1.2 yr.; 160.3 + 3.5 cm; 52.4 + 6.204 kg; 1.56 + 0.09 m^2; 20.57 + 2.23 kg/m^2	HSB	Feet and toes	6.1℃; 80% RH; 0.4 m/s	Sleeping 8 hrs	To evaluate the effectiveness of a smart electrically heated sleeping bag in improving wearers' feet thermal comfort when sleeping under a cool exposure	↔ MR; ↔ HR; ↑ *$\overline{T}_{local(feet)}$; ↔ $\overline{T}_{sk}$; ↑ *TS_{feet}; ↑ *CS_{feet}; ↑ *$CS_{whole\ body}$
Ko et al. (2018)	6 males	22.7 ± 2.0 yr.; 175.6 ± 3.5 cm; 73.1 ± 8.5 kg; 23.6 ± 2.2 kg/m^2	HSB	Feet and toes	23℃; 50% RH	Sleeping 7 hrs	To study the effectiveness of using bed socks in feet warming on sleep quality and thermoregulatory responses in a cold ambient environment	↔ MR; ↔ HR; ↑ *$\overline{T}_{local(feet)}$; ↔ $\overline{T}_{sk}$

Zhang et al. (2016)	3 males	25 ± 1.2 yr.; 174 ± 3.3 cm; 63.9 ± 2.3 kg; 1.77 ± 0.04 m^2; 21.23 ± 0.92 kg/m^2	HSB	Feet and toes	−6.4℃ or 0.5℃; 80% RH; 0.5 m/s	Sleeping 3 hrs	To evaluate the effectiveness of electrically heated sleeping bags in improving the human feet thermal comfort under a cold outdoor environment	↔ MR; ↔ HR; ↑ *$\overline{T}_{local(feet)}$; ↔ $\overline{T}_{sk}$
	3 females	23 ± 2.0 yr.; 160 ± 2.6 cm; 48.2 ± 2.3 kg; 1.48 ± 0.04 m^2; 18.81 ± 0.54 kg/m^2	HSB	Feet and toes	−0.4℃ or 5.5℃; 80% RH; 0.5 m/s	Sleeping 3 hrs		↔ MR; ↔ HR; ↑ *$\overline{T}_{local(feet)}$; ↔ $\overline{T}_{sk}$

***p ≤ 0.05; ** p ≤ 0.01; ***p ≤ 0.005; **** p ≤ 0.001.**

HCP: heating clothes/pad; HSB: heating sleeping bag/socks/ insoles; HV: heating vest.

↑ increased compare HEAT to CON; ↓ decreased compare HEAT to CON; ↔ no change between HEAT and CON.

HR: heart rate; MR: metabolic rate; $\overline{T}_{local}$: mean local temperature; $\overline{T}_{sk}$: mean skin temperature; TS: thermal sensation; CS: comfort sensation.

Publication bias

As noted earlier, funnel plots were applied in assessing the publication bias of the studies by visualizing the distribution of effect size. Figure 3a–e shows the funnel plots of (a) MR, (b) HR, (c) $\overline{T}_{sk}$, (d) TS and (e) CS. The plot in Figures 3a and b show that there is no publication bias in MR and HR since the plot is symmetrical. Lack of bias is also supported by the insignificant value of Fail-safe N ($p>0.05$) and the Begg and Mazumdar rank correlation ($p>0.05$). However, publication bias was revealed in $\overline{T}_{sk}$, TS and CS at ($p<0.05$) by the presence of outliers in the funnel plots.

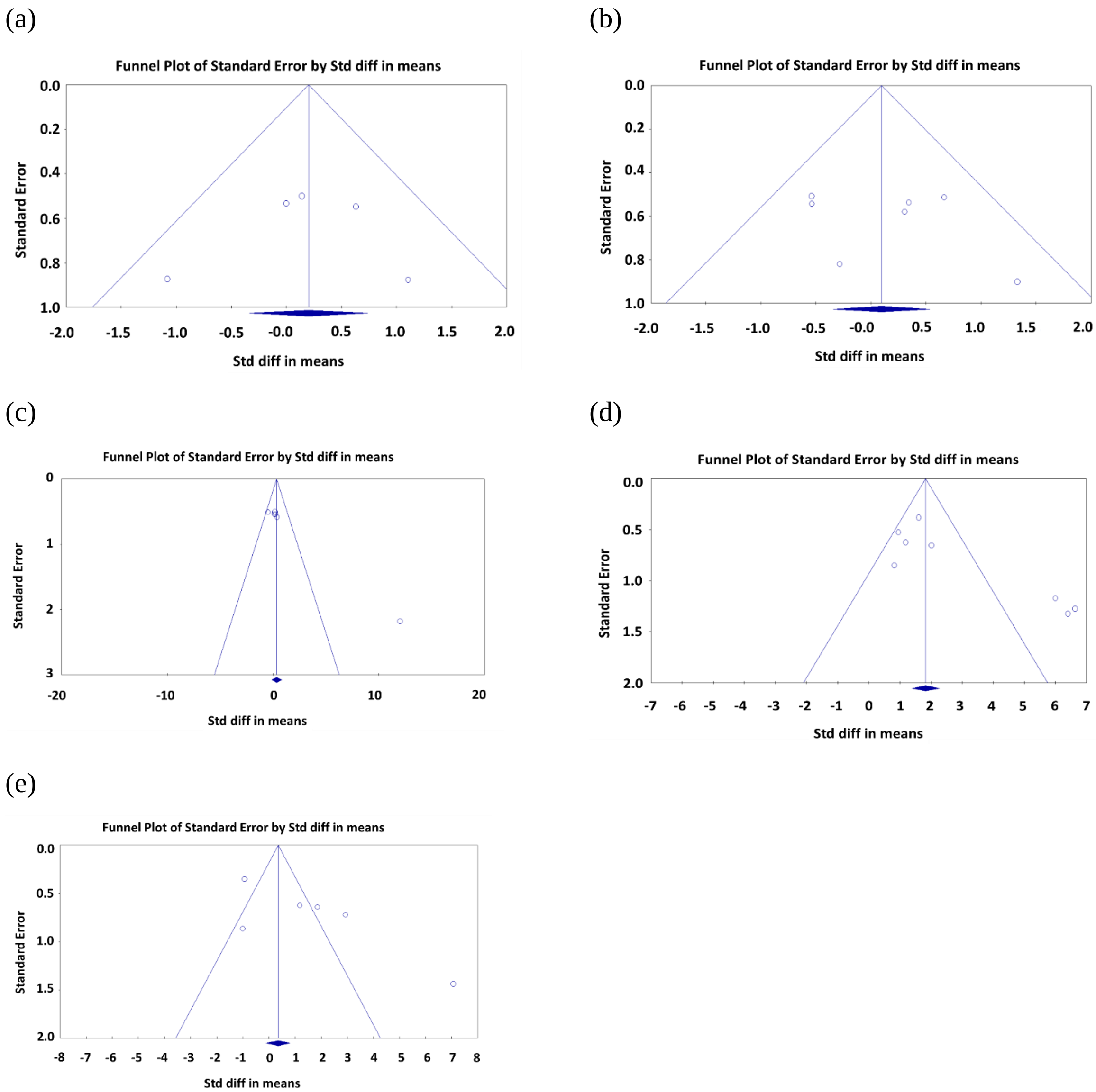


Figure 3. Funnel plots of publication bias: (a) MR, (b) HR, (c) $\overline{T}_{sk}$, (d) TS, and (e) CS.

In terms of heterogeneity, Table 4 below shows the significance of $\overline{T}_{sk}$, TS and CS ($p<0.1$) with I^2 >75% but no heterogeneity ($p>0.1$) is shown in MR and HR with I^2<25%. Therefore, the random-effect model can be applied to calculate the pooled intervention effect of $\overline{T}_{sk}$, TS and CS. In contrast, the fixed effect model can be applied to calculate the intervention effect of MR and HR.

Table 4. Result of the meta-analysis.

	Model		Effect size and 95% confidence interval					Test of null (2-Tail)		Heterogeneity				Tau-squared			
	Model	Number Studies	Point estimate	Standard error	Variance	Lower limit	Upper limit	Z-value	P-value	Q-value	df(Q)	P-value	I-squared	Tau Squared	Standard Error	Variance	Tau
MR	Fixed	5	0.201	0.273	0.074	−0.333	0.736	0.738	0.461	3.987	4	0.408	0.000	0.000	0.276	0.076	0.000
	Random	5	0.201	0.273	0.074	−0.333	0.736	0.738	0.461								
HR	Fixed	7	0.097	0.223	0.050	−0.340	0.534	0.436	0.663	6.579	6	0.362	8.804	0.034	0.225	0.050	0.185
	Random	7	0.101	0.235	0.055	−0.359	0.561	0.432	0.666								
$\overline{\mathbf{T}}_{\mathbf{sk}}$	Fixed	7	0.353	0.234	0.055	−0.107	0.812	1.505	0.132	60.078	6	0.000	90.013	3.681	2.730	7.453	1.919
	Random	7	1.981	0.817	0.668	0.379	3.582	2.424	0.015								
TS	Fixed	9	1.834	0.224	0.050	1.394	2.273	8.182	0.000	45.768	8	0.000	82.520	2.346	1.673	2.800	1.532
	Random	9	2.589	0.585	0.342	1.442	3.735	4.426	0.000								
CS	Fixed	7	0.354	0.235	0.055	−0.106	0.814	1.509	0.131	60.327	6	0.000	90.054	4.039	3.049	9.294	2.010
	Random	7	1.241	0.819	0.671	−0.364	2.846	1.516	0.130								

Effectiveness of e-textiles on primary outcomes

Table 5 below summarises SMD at 95% CI to evaluate the effect of employing heating e-textiles on HR, MR, $\overline{T}_{local}$, $\overline{T}_{sk}$, TS and CS by comparing the HEAT and CON, i.e., changes Δ. The pooled data were separated according to gender.

In terms of metabolic response, only three out of eight studies mentioned ΔMR and all were concerned with feet and toes.[8–10] By separating the data collected from the different genders, five outcomes of three studies were extracted with the overall results: SMD = 0.201, 95% CI: −0.333 to 0.736, p = 0.461. On the other hand, seven sets of pooled data, all focusing on heating the feet and toes except one for feet, buttocks and shoulders, were collected from five papers regarding ΔHR.[8–10,15,16] The overall effective size was relatively small compared to ΔMR, where SMD = 0.097, 95% CI: −0.340 to 0.534, p = 0.663. No significant difference in ΔMR and ΔHR at $p>0.05$ was found.

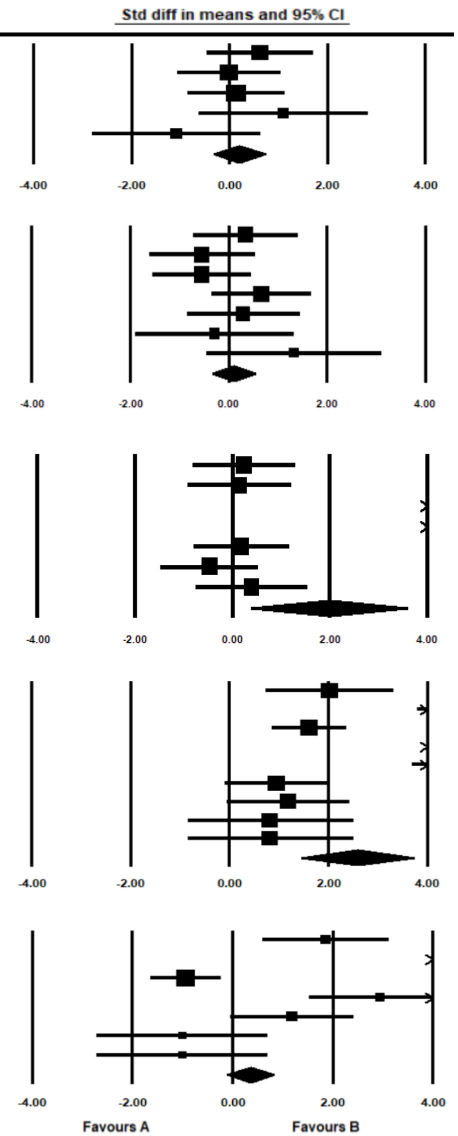
In the case of thermo-regulatory response, seven valid data sets for $\Delta\overline{T}_{sk}$ were extracted from five research articles for analysis.[5,8,10,15,16] The overall results were SMD = 1.981, 95% CI: 0.379 to 3.582 p = 0.015. The variance among the studies was small at 0.25–0.34 except in the case of heating the upper torso at 4.763.[5] The overall large effect size is significant at $p<0.05$ and can be attributed to an extremely high effect size in the study, i.e., SMD = 12.017.

With regard to perceptual response, nine sets of results were collected from six studies for ΔTS analysis.[4,5,8–10,16] The overall results were SMD = 2.589, 95% CI:1.442 to 3.735, p = 0.000. For ΔCS, seven sets from five studies were available.[4,8–10,16] The effect size was much smaller than ΔTS, where SMD = 0.354, 95% CI: −0.106 to 0.814, p = 0.131. In terms of p-value, the result for ΔTS (0.000) was significant at $p<0.05$, while the result for ΔCS (0.131) was not.

The overall results showed that heating by an e-textile provided a large effect in terms of thermal sensation (2.589), a moderate effect for mean skin temperature (1.981), a mild effect for comfort sensation (0.354) and metabolic rate (0.201), and almost no change for heart rate (0.097).

Table 5. Standard mean differences among study results.

	Study name	Gender	Heated body part	Statistics for each study: Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Sample size: MR(Exp)	MR(Con)
MR	Song et al. 2016	Female	Feet and toes	0.632	0.548	0.300	−0.441	1.706	1.155	0.248	7	7
	Song et al. 2016	Male	Feet and toes	0.000	0.535	0.286	−1.048	1.048	0.000	1.000	7	3
fixed	Zhang et al. 2017	Female	Feet and toes	0.142	0.501	0.251	−0.839	1.124	0.285	0.776	8	8
effect	Zhang et al. 2016	Female	Feet and toes	1.107	0.877	0.769	−0.612	2.825	1.262	0.207	3	3
model	Zhang et al. 2016	Male	Feet and toes	−1.079	0.874	0.764	−2.791	0.634	−1.234	0.217	3	3
				0.201	**0.273**	**0.074**	**−0.333**	**0.736**	**0.738**	**0.461**		
HR	Song et al. 2016	Female	Feet and toes	0.346	0.539	0.290	−0.709	1.402	0.643	0.520	7	7
	Song et al. 2016	Male	Feet and toes	−0.537	0.544	0.296	−1.603	0.530	−0.987	0.324	7	7
fixed effect	Song et al. 2020	Female	Feet, buttocks and shoulders	−0.538	0.509	0.259	−1.536	0.459	−1.057	0.290	8	8
model	Zhang et al. 2017	Female	Feet and toes	0.667	0.514	0.264	−0.340	1.674	1.298	0.194	8	8
	Ko et al. 2018	Male	Feet and toes	0.307	0.581	0.337	−0.831	1.445	0.528	0.597	6	6
	Zhang et al. 2016	Female	Feet and toes	−0.283	0.821	0.673	−1.891	1.325	−0.345	0.730	3	3
	Zhang et al. 2016	Male	Feet and toes	1.333	0.903	0.815	−0.436	3.103	1.477	0.140	3	3
				0.097	**0.223**	**0.050**	**−0.340**	**0.534**	**0.436**	**0.663**		
$\overline{T}_{sk}$	Song et al. 2016	Female	Feet and toes	0.235	0.536	0.288	−0.816	1.286	0.438	0.661	7	7
	Song et al. 2016	Male	Feet and toes	0.141	0.535	0.286	−0.908	1.190	0.264	0.792	7	7
random	Sormunen et al. 2009	Female	Upper torso	12.017	2.182	4.763	7.739	16.294	5.506	0.000	8	8
effect	Sormunen et al. 2009	Male	Upper torso	12.017	2.182	4.763	7.739	16.294	5.506	0.000	8	8
model	Song et al. 2020	Female	Feet, buttocks and shoulders	0.184	0.501	0.251	−0.798	1.167	0.368	0.713	8	8
	Zhang et al. 2017	Female	Feet and toes	−0.468	0.507	0.257	−1.461	0.525	−0.924	0.356	8	8
	Ko.et al. 2018	Male	Feet and toes	0.392	0.583	0.340	−0.750	1.535	0.673	0.501	6	6
				1.981	**0.817**	**0.668**	**0.379**	**3.582**	**2.424**	**0.015**		
TS	Song et al. 2016	Female	Feet and toes	2.025	0.657	0.432	0.736	3.313	3.080	0.002	7	7
	Song et al. 2016	Male	Feet and toes	6.412	1.324	1.754	3.816	9.008	4.841	0.000	7	7
random	Kim et al. 2021	Both	Upper torso	1.613	0.384	0.147	0.861	2.365	4.204	0.000	18	18
effect	Sormunen et al. 2009	Female	Upper torso	6.641	1.276	1.628	4.140	9.142	5.204	0.000	8	8
model	Sormunen et al. 2009	Male	Upper torso	6.008	1.174	1.378	3.707	8.309	5.118	0.000	8	8
	Zhang et al. 2017	Female	Feet and toes	0.962	0.528	0.279	−0.074	1.997	1.821	0.069	8	8
	Ko.et al. 2018	Male	Feet and toes	1.192	0.627	0.393	−0.036	2.420	1.903	0.057	6	6
	Zhang et al. 2016	Female	Feet and toes	0.829	0.851	0.724	−0.839	2.497	0.974	0.330	3	3
	Zhang et al. 2016	Male	Feet and toes	0.829	0.851	0.724	−0.839	2.497	0.974	0.330	3	3
				2.589	**0.585**	**0.342**	**1.442**	**3.735**	**4.426**	**0.000**		
CS	Song et al. 2016	Female	Feet and toes	1.867	0.641	0.410	0.612	3.123	2.915	0.004	7	7
	Song et al. 2016	Male	Feet and toes	7.071	1.439	2.071	4.250	9.892	4.913	0.000	7	7
random	Kim et al. 2021	Both	Upper torso	−0.930	0.351	0.123	−0.618	−0.242	−2.651	0.008	18	18
effect	hang et al. 2017	Female	Feet and toes	2.946	0.722	0.521	1.531	4.362	4.081	0.000	8	8
model	Ko.et al. 2018	Male	Feet and toes	1.192	0.627	0.393	−0.036	2.420	1.903	0.057	6	6
	Zhang et al. 2016	Female	Feet and toes	−1.000	0.866	0.750	−2.697	0.697	−1.155	0.248	3	3
	Zhang et al. 2016	Male	Feet and toes	−1.000	0.866	0.750	−2.697	0.697	−1.155	0.248	3	3
				0.354	**0.235**	**0.055**	**−0.106**	**0.814**	**1.509**	**0.131**		



Gender comparison

Table 6 below compares the effects of heating e-textiles on the genders, showing SMD between HEAT and CON in terms of gender difference. The overall changes in metabolic response were small and insignificant at $p>0.05$. For ΔMR, heating e-textiles recorded a larger effect on females (SMD = 0.477, 95% CI: −0.190 to 1.145, p = 0.161) than males (SMD = −0.294, 95% CI: −1.187 to 0.600, p = 0.520). In other words, in the application of heating e-textiles, females result in larger impact in increasing MR than males. The effect size for both genders was similar for ΔHR, i.e., males with SMD = 0.097, 95% CI: −0.616 to 0.809, p = 0.790 and females with SMD = 0.097, 95% CI: −0.455 to 0.650, p = 0.730.

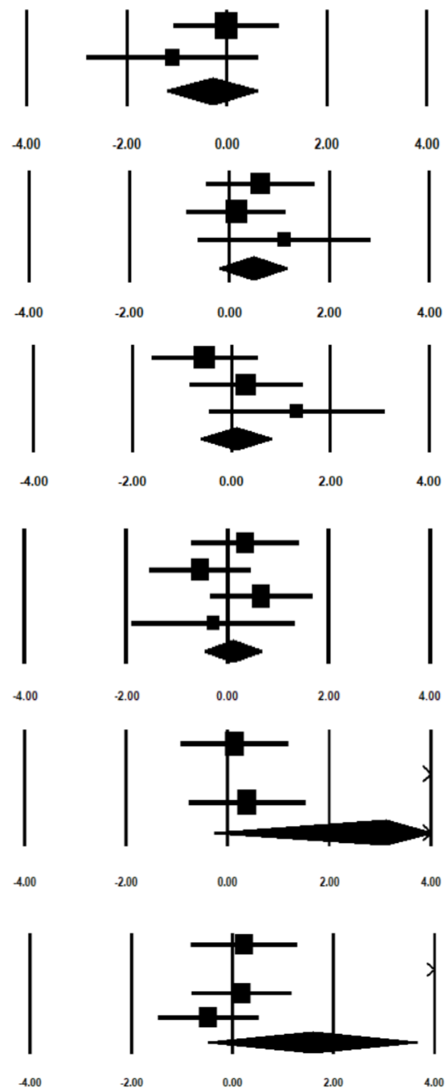
With regard to $\Delta\overline{T}_{sk}$ thermo-regulatory response, the change was significant in males at $p<0.05$ (SMD = 3.105, 95% CI: −0.268 to 6.477, p = 0.071). The thermo-regulatory response of males was larger than that of females (SMD = 1.586, 95% CI: −0.480 to 3.653, p = 0.132).

In the case of perceptual response, the results show that the heating effectiveness of e-textiles significantly improved thermal sensation in both genders but was insignificant in terms of comfort sensation. This result is supported by the evidence that at $p<0.05$ ΔTS for males recorded (SMD = 3.439, 95% CI: 0.737 to 6.141at p = 0.013), females (SMD = 2.343, 95% CI: 0.490 to 4.195, p = 0.013) and for both genders (SMD = 1.613, 95% CI: 0.861 to 2.365, p = 0.000). For ΔCS for males at $p>0.05$ (SMD = 2.210, 95% CI: −1.324 to 5.743, p = 0.220), females (SMD = 1.326, 95% CI: −0.775 to 3.427, p = 0.216) but at $p<0.05$ for both genders (SMD = −0.930, 95% CI: −0.618 to −0.242, p = 0.008). Overall, males recorded a larger effect than females for perceptual response in terms of ΔTS (males: 3.439; females: 2.343) and ΔCS (males: 2.210; females: 1.326).

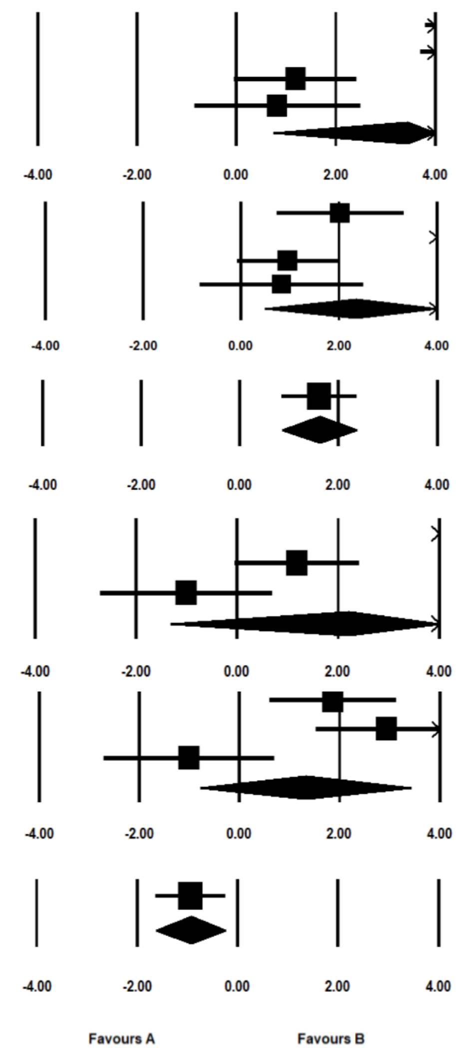
Table 6. Standard mean differences of results by gender.

	Study name	Gender	Heated body part	Statistics for each study							Sample size	
				Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	MR(Exp)	MR(Con)
MR	**Male**											
	Song et al. 2016	Male	Feet and toes	0.000	0.535	0.286	−1.048	1.048	0.000	1.000	7	3
fixed effect model	Zhang et al. 2016	Male	Feet and toes	−1.079	0.874	0.764	−2.791	0.634	−1.234	0.217	3	3
				−0.294	**0.456**	**0.208**	**−1.187**	**0.600**	**−0.644**	**0.520**		
	Female											
	Song et al. 2016	Female	Feet and toes	0.632	0.548	0.300	−0.441	1.706	1.155	0.248	7	7
	Zhang et al. 2017	Female	Feet and toes	0.142	0.501	0.251	−0.839	1.124	0.285	0.776	8	8
	Zhang et al. 2016	Female	Feet and toes	1.107	0.877	0.769	−0.612	2.825	1.262	0.207	3	3
				0.477	**0.341**	**0.116**	**−0.190**	**1.145**	**1.402**	**0.161**		
HR	**Male**											
	Song et al. 2016	Male	Feet and toes	−0.537	0.544	0.296	−1.603	0.530	−0.987	0.324	7	7
fixed effect model	Ko et al. 2018	Male	Feet and toes	0.307	0.581	0.337	−0.831	1.445	0.528	0.597	6	6
	Zhang et al. 2016	Male	Feet and toes	1.333	0.903	0.815	−0.436	3.103	1.477	0.140	3	3
				0.097	**0.363**	**0.132**	**−0.616**	**0.809**	**0.266**	**0.790**		
	Female											
	Song et al. 2016	Female	Feet and toes	0.346	0.539	0.290	−0.709	1.402	0.643	0.520	7	7
	Song et al. 2020	Female	Feet, buttocks and shoulders	−0.538	0.509	0.259	−1.536	0.459	−1.057	0.290	8	8
	Zhang et al. 2017	Female	Feet and toes	0.667	0.514	0.264	−0.340	1.674	1.298	0.194	8	8
	Zhang et al. 2016	Female	Feet and toes	−0.283	0.821	0.673	−1.891	1.325	−0.345	0.730	3	3
				0.097	**0.282**	**0.079**	**−0.455**	**0.650**	**0.345**	**0.730**		
$\overline{T}_{sk}$	**Male**											
	Song et al. 2016	Male	Feet and toes	0.141	0.535	0.286	−0.908	1.190	0.264	0.792	7	7
random effect model	Sormunen et al. 2009	Male	Upper torso	12.017	2.182	4.763	7.739	16.294	5.506	0.000	8	8
	Ko.et al. 2018	Male	Feet and toes	0.392	0.583	0.340	−0.750	1.535	0.673	0.501	6	6
				3.105	**1.721**	**2.960**	**−0.268**	**6.477**	**1.804**	**0.071**		
	Female											
	Song et al. 2016	Female	Feet and toes	0.235	0.536	0.288	−0.816	1.286	0.438	0.661	7	7
	Sormunen et al. 2009	Female	Upper torso	12.017	2.182	4.763	7.739	16.294	5.506	0.000	8	8
	Song et al. 2020	Female	Feet, buttocks and shoulders	0.184	0.501	0.251	−0.798	1.167	0.368	0.713	8	8
	Zhang et al. 2017	Female	Feet and toes	−0.468	0.507	0.257	−1.461	0.525	−0.924	0.356	8	8
				1.586	**1.055**	**1.112**	**−0.480**	**3.653**	**1.504**	**0.132**		

Std diff in means and 95% CI



TS	**Male**											
	Song et al. 2016	Male	Feet and toes	6.412	1.324	1.754	3.816	9.008	4.841	0.000	7	7
random effect model	Sormunen et al. 2009	Male	Upper torso	6.008	1.174	1.378	3.707	8.309	5.118	0.000	8	8
	Ko.et al. 2018	Male	Feet and toes	1.192	0.627	0.393	−0.036	2.420	1.903	0.057	6	6
	Zhang et al. 2016	Male	Feet and toes	0.829	0.851	0.724	−0.839	2.497	0.974	0.330	3	3
				3.439	**1.379**	**1.901**	**0.737**	**6.141**	**2.494**	**0.013**		
	Female											
	Song et al. 2016	Female	Feet and toes	2.025	0.657	0.432	0.736	3.313	3.080	0.002	7	7
	Sormunen et al. 2009	Female	Upper torso	6.641	1.276	1.628	4.140	9.142	5.204	0.000	8	8
	Zhang et al. 2017	Female	Feet and toes	0.962	0.528	0.279	−0.074	1.997	1.821	0.069	8	8
	Zhang et al. 2016	Female	Feet and toes	0.829	0.851	0.724	−0.839	2.497	0.974	0.330	3	3
				2.343	**0.945**	**0.894**	**0.490**	**4.195**	**2.478**	**0.013**		
	Both											
	Kim et al. 2021	Both	Upper torso	1.613	0.384	0.147	0.861	2.365	4.204	0.000	18	18
				1.613	**0.384**	**0.147**	**0.861**	**2.365**	**4.204**	**0.000**		
CS	**Male**											
	Song et al. 2016	Male	Feet and toes	7.071	1.439	2.071	4.250	9.892	4.913	0.000	7	7
random effect model	Ko.et al. 2018	Male	Feet and toes	1.192	0.627	0.393	−0.036	2.420	1.903	0.057	6	6
	Zhang et al. 2016	Male	Feet and toes	−1.000	0.866	0.750	−2.697	0.697	−1.155	0.248	3	3
				2.210	**1.803**	**3.251**	**−1.324**	**5.743**	**1.226**	**0.220**		
	Female											
	Song et al. 2016	Female	Feet and toes	1.867	0.641	0.410	0.612	3.123	2.915	0.004	7	7
	Zhang et al. 2017	Female	Feet and toes	2.946	0.722	0.521	1.531	4.362	4.081	0.000	8	8
	Zhang et al. 2016	Female	Feet and toes	−1.000	0.866	0.750	−2.697	0.697	−1.155	0.248	3	3
				1.326	**1.072**	**1.149**	**−0.775**	**3.427**	**1.237**	**0.216**		
	Both											
	Kim et al. 2021	Both	Upper torso	−0.930	0.351	0.123	−0.618	−0.242	−2.651	0.008	18	18
				−0.930	**0.351**	**0.123**	**−0.618**	**−0.242**	**−2.651**	**0.008**		



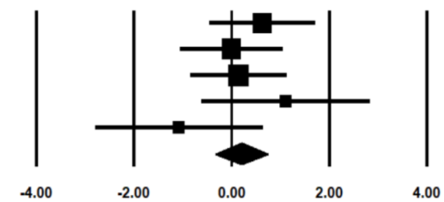
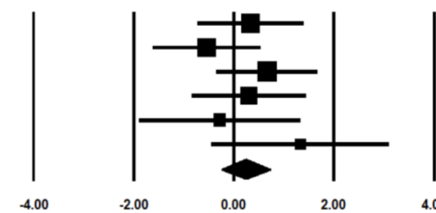
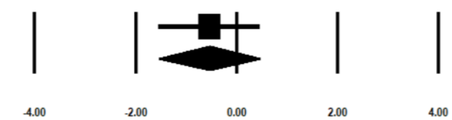
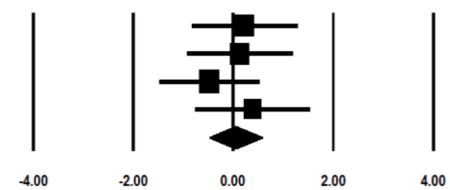
Comparison of heated body regions

Table 7 below presents a comparison of the results for heated body regions. Only three studies with five valid sets of pooled data reported ΔMR in metabolic responses and all focused on the heating of feet and toes. The effect size was small and insignificant ($p>0.05$) with SMD = 0.201, 95% CI: –0.333 to 0.736, p = 0.461. There were seven valid pooled data sets from studies focusing on heating feet and toes and one in the ΔHR analysis reporting on heating feet, buttocks and shoulders. The effect size was insignificant ($p>0.05$) for heating feet and toes (SMD = 0.248, 95% CI: –0.238 to 0.733, p = 0.318) and also for heating feet, buttocks and shoulder (SMD = –0.538, 95% CI: –1.536 to 0.459, p = 0.290).

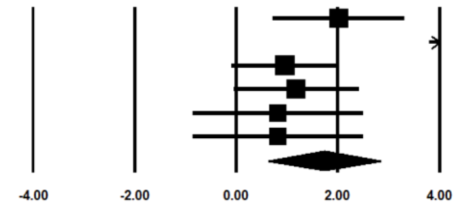
Regarding $\Delta\overline{T}_{sk}$ in thermo-regulatory responses, there were four valid data for heating feet and toes; one for feet, buttocks and shoulders; and two for upper torso. The effect size for heating the upper torso was very large and significant (SMD = 12.017, 95% CI: 8.992 to 15.041, p = 0.000) compared to the insignificant result for both heating feet and toes (SMD = 0.047, 95% CI: –0.481 to 0.574, p = 0.863) and feet, buttocks and shoulders (SMD = 0.184, 95% CI: –0.798 to 1.167, p = 0.713).

The results showed significant improvement of perceptual response in thermal sensation and comfort sensation in heating feet and toes, and the upper torso. In terms of ΔTS, heating the upper torso (SMD = 4.614, 95% CI: 0.916 to 8.311, p = 0.014) produced a much larger improvement than heating feet and toes (SMD = 1.730, 95% CI: 0.627 to 2.832, p = 0.002). There was also improvement in comfort sensation in heating feet and toes (SMD = 1.652, 95% CI: –0.065 to 3.370, p = 0.059) but no enhancement was noted in heating the upper torso (SMD = −0.930, 95% CI: −0.618 to −0.242, p = 0.008).

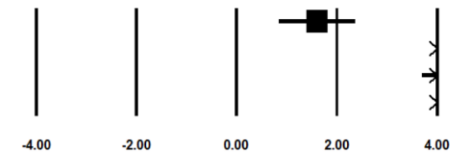
Table 7. Standard mean difference of results by body region.

	Study name	Gender	Heated body part	Statistics for each study							Sample size		Std diff in means and 95% CI
				Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	MR(Exp)	MR(Con)	
MR	**Feet and toes**												
	Song et al. 2016	Female	Feet and toes	0.632	0.548	0.300	−0.441	1.706	1.155	0.248	7	7	
fixed effect model	Song et al. 2016	Male	Feet and toes	0.000	0.535	0.286	−1.048	1.048	0.000	1.000	7	3	
	Zhang et al. 2017	Female	Feet and toes	0.142	0.501	0.251	−0.839	1.124	0.285	0.776	8	8	
	Zhang et al. 2016	Female	Feet and toes	1.107	0.877	0.769	−0.612	2.825	1.262	0.207	3	3	
	Zhang et al. 2016	Male	Feet and toes	−1.079	0.874	0.764	−2.791	0.634	−1.234	0.217	3	3	
				0.201	**0.273**	**0.074**	**−0.333**	**0.736**	**0.738**	**0.461**			
HR	**Feet and toes**												
	Song et al. 2016	Female	Feet and toes	0.346	0.539	0.290	−0.709	1.402	0.643	0.520	7	7	
fixed effect model	Song et al. 2016	Male	Feet and toes	−0.537	0.544	0.296	−1.603	0.530	−0.987	0.324	7	7	
	Zhang et al. 2017	Female	Feet and toes	0.667	0.514	0.264	−0.340	1.674	1.298	0.194	8	8	
	Ko et al. 2018	Male	Feet and toes	0.307	0.581	0.337	−0.831	1.445	0.528	0.597	6	6	
	Zhang et al. 2016	Female	Feet and toes	−0.283	0.821	0.673	−1.891	1.325	−0.345	0.730	3	3	
	Zhang et al. 2016	Male	Feet and toes	1.333	0.903	0.815	−0.436	3.103	1.477	0.140	3	3	
				0.248	**0.248**	**0.061**	**−0.238**	**0.733**	**0.999**	**0.318**			
	Feet, buttocks and shoulders												
	Song et al. 2020	Female	Feet, buttocks and shoulders	−0.538	0.509	0.259	−1.536	0.459	−1.057	0.290	8	8	
				−0.538	**0.509**	**0.259**	**−1.536**	**0.459**	**−1.057**	**0.290**			
$\overline{T}_{sk}$	**Feet and toes**												
	Song et al. 2016	Female	Feet and toes	0.235	0.536	0.288	−0.816	1.286	0.438	0.661	7	7	
random effect model	Song et al. 2016	Male	Feet and toes	0.141	0.535	0.286	−0.908	1.190	0.264	0.792	7	7	
	Zhang et al. 2017	Female	Feet and toes	−0.468	0.507	0.257	−1.461	0.525	−0.924	0.356	8	8	
	Ko.et al. 2018	Male	Feet and toes	0.392	0.583	0.340	−0.750	1.535	0.673	0.501	6	6	
				0.047	**0.269**	**0.072**	**−0.481**	**0.574**	**0.173**	**0.863**			
	Feet, buttocks and shoulders												
	Song et al. 2020	Female	Feet, buttocks and shoulders	0.184	0.501	0.251	−0.798	1.167	0.368	0.713	8	8	
				0.184	**0.501**	**0.251**	**−0.798**	**1.167**	**0.368**	**0.713**			
	Upper torso												
	Sormunen et al. 2009	Female	Upper torso	12.017	2.182	4.763	7.739	16.294	5.506	0.000	8	8	
	Sormunen et al. 2009	Male	Upper torso	12.017	2.182	4.763	7.739	16.294	5.506	0.000	8	8	
				12.017	**1.543**	**2.381**	**8.992**	**15.041**	**7.787**	**0.000**			

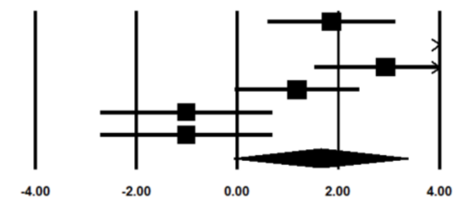
TS	**Feet and toes**										
	Song et al. 2016	Female	Feet and toes	2.025	0.657	0.432	0.736	3.313	3.080	0.002	7	7
random effect model	Song et al. 2016	Male	Feet and toes	6.412	1.324	1.754	3.816	9.008	4.841	0.000	7	7
	Zhang et al. 2017	Female	Feet and toes	0.962	0.528	0.279	−0.074	1.997	1.821	0.069	8	8
	Ko.et al. 2018	Male	Feet and toes	1.192	0.627	0.393	−0.036	2.420	1.903	0.057	6	6
	Zhang et al. 2016	Female	Feet and toes	0.829	0.851	0.724	−0.839	2.497	0.974	0.330	3	3
	Zhang et al. 2016	Male	Feet and toes	0.829	0.851	0.724	−0.839	2.497	0.974	0.330	3	3
				1.730	**0.562**	**0.316**	**0.627**	**2.832**	**3.075**	**0.002**		



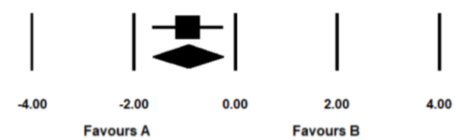
	Upper torso										
	Kim et al. 2021	Both	Upper torso	1.613	0.384	0.147	0.861	2.365	4.204	0.000	18	18
	Sormunen et al. 2009	Female	Upper torso	6.641	1.276	1.628	4.140	9.142	5.204	0.000	8	8
	Sormunen et al. 2009	Male	Upper torso	6.008	1.174	1.378	3.707	8.309	5.118	0.000	8	8
				4.614	**1.887**	**3.559**	**0.916**	**8.311**	**2.446**	**0.014**		



CS	**Feet and toes**										
	Song et al. 2016	Female	Feet and toes	1.867	0.641	0.410	0.612	3.123	2.915	0.004	7	7
random effect model	Song et al. 2016	Male	Feet and toes	7.071	1.439	2.071	4.250	9.892	4.913	0.000	7	7
	Zhang et al. 2017	Female	Feet and toes	2.946	0.722	0.521	1.531	4.362	4.081	0.000	8	8
	Ko.et al. 2018	Male	Feet and toes	1.192	0.627	0.393	−0.036	2.420	1.903	0.057	6	6
	Zhang et al. 2016	Female	Feet and toes	−1.000	0.866	0.750	−2.697	0.697	−1.155	0.248	3	3
	Zhang et al. 2016	Male	Feet and toes	−1.000	0.866	0.750	−2.697	0.697	−1.155	0.248	3	3
				1.652	**0.876**	**0.768**	**−0.065**	**3.370**	**1.885**	**0.059**		



	Upper torso										
	Kim et al. 2021	Both	Upper torso	−0.930	0.351	0.123	−0.618	−0.242	−2.651	0.008	18	18
				−0.930	**0.351**	**0.123**	**−0.618**	**−0.242**	**−2.651**	**0.008**		



Discussion

This study provides fundamental evidence-based points of reference for future smart textile development. The effectiveness of heating e-textiles on improving human thermal comfort has been largely ignored, and this knowledge gap has to some extent been filled by this review. Heating interventions in eligible studies were investigated and categorised into three types of heated e-textile, i.e., HCP (12.5%) for heating feet, buttocks and shoulders, HSB (62.5%) for heating feet and toes and HV (25%) for heating the upper torso. In the meta-analysis, the pooled data collected on physiological measurement and subjective evaluation were analyzed in subgroups to permit comparison between the genders and heated body regions respectively.

Effects of various types of heated e-textile

In comparing CON and HEAT, a significant change in thermo-regulatory response was noted, which can be attributed to the very large effect reported in the study of heating the upper torso. With regard to perceptual response, the results also showed significant improvements in thermal sensation. The overall data indicated that heating e-textiles had a large effect on thermal sensation, a moderate effect on mean skin temperature, a mild effect on comfort sensation and metabolic rate, and almost no effect on heart rate.

The insignificant effects on metabolic rate and heart rate reported in the findings demonstrate that most of the heated e-textiles used in the studies are safe and useful. Since a heating textile makes direct contact with the skin surface, a moderate effect on mean skin temperature was expected. However, the mild improvement reported for comfort sensation was unexpected, particularly since thermal sensation showed significant improvement. The unexpected outcome for comfort sensation may be attributed to the texture of the fabric making direct skin contact. Fabric texture should be investigated and a more satisfactory one developed as necessary. The improvement of the fabric could be achieved by selection of soft and downy materials to increase hand feel and modification of the fabric structure to increase permeability. KES testing equipment could be used for bio-sensory evaluation of functional fabrics by testing the fabric for the properties of compression, tensile and shear, friction, bending and air permeability. KES testing should be carried out prior to live trial testing.

Effects of heating e-textiles on different genders

A trial test in the literature reported gender variation in change of skin temperature and conductive heat flux. The findings show that females recorded lower conductive heat flux but higher local skin temperature at several body positions, including chest, back, abdomen, waist and legs than males in a cold environment without heating intervention.[22] The study summarized this result without mentioning the attribution to a woman's menstrual period. Therefore, it may also be the research gap for future study. Smaller thermal sensitivity differences have also been observed between males and females.[23] This reflects partially findings in the present study indicating a significant enhancement in thermal response for males compared to females. However, the thermo-regulatory response in terms of mean skin temperature at several local body parts, including upper torso, feet and toes in this study recorded a significantly larger effect for males than females. The differences between results reported in the literature and in the present study may be due to the heating intervention. In literature, females recorded higher local skin temperature than males in a cold environment without heating intervention. In the analyzed results of this study, males recorded higher local skin temperature than females in a cold ambient environment with heating intervention of e-textiles. It can also be concluded that the local skin temperature in upper torso and legs of males increases in a larger extend than the one of females when heated by e-textiles. This finding needs further investigation but is clearly important in informing the development of novel smart thermal textiles based on customized and gender-differentiated designs with the aid of artificial intelligence (AI). By collecting raw data of thermo-regulatory response in terms of mean skin temperature as well as the thermal sensitivity and thermal comfort of different genders and ages, a database could be created. An AI model could then be trained to provide the optimal heating levels to different genders to achieve and maximize the satisfaction in thermal comfort.

It would also be valuable to investigate the heating effectiveness of e-textiles on different age groups and discover the optimal heating temperature for specified groups, such as infants, children, adults and the elderly. Since different age groups possess record different thermal sensations, having a comprehensive systematic review of a variety of age groups is vital for the future development of smart thermal textiles.

Effects on heated body regions

A variety of heated e-textiles have been fabricated and targeted at different age groups of users and specific body regions. The most common heating interventions for cold protection are the heating vest and clothes in daily use and heating blankets for sleeping.

Regarding thermo-regulatory response, a much larger and significant effect size in heating the upper torso was noted. Also, the findings indicate a significant improvement in perceptual response in terms of thermal sensation and comfort sensation in heating feet and toes, and the upper torso. These results show that the upper torso is the most receptive body region for generating satisfaction with the thermal comfort provided by heating e-textiles. Although only two relevant studies were compared in the meta-analysis, still the final outcomes are supported by several other studies which investigated thermal body mapping. The findings showed that the leg and back are the regions that show high thermal sensitivity, with the back of the torso and the central back showing the highest sensation.[22–25] This indicates that there is a positive correlation between thermal sensitivity and thermal comfort. In order to maintain daily routines in cold environment, it is clearly important to keep the torso warm. That is the reason for positioning heating pads mainly at the back of the torso in heating vests and other clothes. Unlike everyday heating garments, novel sleeping bag prototypes have been developed in recent years, which aim at warming the feet and toes. According to the thermal body mapping, legs have relatively low thermal sensitivity, but there is a good reason for warming the feet and toes at night. It is believed that limbs feel the cold during sleep in a cold environment. Warming feet and toes in a sleeping bag improves blood circulation in that region, and this enhances thermal comfort and sleep.

In fact, the two heating interventions described above apply in different situations, i.e., day and night. Although the thermal body mapping in the studies reviewed claimed that the thermal sensitivity of the feet and toes is relatively low, this present meta-analysis shows that heating the feet and toes produces a significant improvement in perceptual response.

Limitations and directions for future research

An obvious limitation is that only a small number of studies were eligible for inclusion in the review. Only eight research articles met the criteria for inclusion and the number of participants in the majority of studies was less than 10 males and females. It is recognized that this limitation may result in a degree of publication bias. Furthermore, some studies lacked detailed participant information in terms of mean ± SD, such as age (yr), height (cm) weight (kg), body surface area (m^2); body mass index (kg/m^2) and primary outcomes (i.e., MR, HR, $\overline{T}_{sk}$, TS and CS), resulting in incomplete data extraction for comparison, calculation and further analysis. Due to this lack of information, the review was unable to explore the common heating temperature range of e-textiles in cold environments. Most of the studies included in the review expressed results of the heating efficiency of e-textiles in terms of users' responses without providing the actual heating temperature of the intervention.

The studies also failed to provide detailed specifications of the heating intervention, such as heating distribution expressed as a thermal image. The range of ambient testing conditions in cold environments have been restricted in this review for comparison and analysis, but considerable variation was present in the studies of up to 10℃; that is, from –6.4 to 6.1℃ (except one case of 23℃).

A set of standardized testing conditions is needed to permit accurate reproduction and comparison of results. Testing protocol variation among the studies, with (1) static mode, standing and resting, (2) activity with body movement, such as moving heavy objects or running and (3) sleeping, may also affect the test outcomes since some of the protocols lacked precise details.

Although there were several limitations in this study, the analyzed results of this systematic review and meta-analysis still serve as vital references for further development of smart heating textile-technology. This research found that (1) feet and toes, (2) feet, buttocks and shoulders, and (3) the upper torso are the common body parts being heated to achieve thermal comfort. While, the heating intervention of heating textiles significantly improved $\Delta\overline{T}_{sk}$ and ΔTS ($p<0.05$) comparing CON to HEAT. In terms of gender, there was a significantly improvement in $\Delta\overline{T}_{sk}$ for males and ΔTS for both genders ($p<0.05$). Regarding to the body regions, there was also a significant effect on $\Delta\overline{T}_{sk}$, ΔTS and ΔCS in heating the upper torso as well as ΔTS in heating feet and toes ($p<0.05$). That means upper torso, feet and toes would be the main heating body regions to achieve human thermal comfort when developing the intelligent heating textiles in AI approach in future. Since different heating temperature might be required at different body parts, the intelligent heating textiles could be fabricated in general textile products in form of cushion, or heating wearables to allow the users to select different modes in warming specified body parts. Besides, when collecting data from genders to build dataset for AI training, it is predicted that males respond in higher $\Delta\overline{T}_{sk}$ compared to females when they are heated by the same temperature level.

Conclusion

This article has reported a systematic review and meta-analysis of relevant studies on the effectiveness of heating e-textiles on human thermal comfort in different subgroups, in which the moderators were gender and body regions. In the part of systematic review, PRISMA was applied as a checklist for screening the published literature in terms of certain eligibility criteria. There was a four-stage process to collect eligible data according to PICO, including identification, screening, qualification and inclusion. Inclusion criteria for the studies included: (1) Healthy participants in age group ranged 20–30 year-old. (2) Interventions of heating e-textiles applied only in trial tests that subjects were running, walking, standing or sitting. (3) Environment that tests were conducted in a climate chamber with controllable ambient temperature, relative humidity and air velocity. (4) Comparison groups included HEAT and CON groups figured in the eligible studies; Study methods using both the blind method and RCT. (5) Outcome measures included objective measurement, thermo-regulatory response and perceptual response. In the part of meta-analysis, the study found that the common body parts heated by e-textiles in the studies were (1) feet and toes, (2) feet, buttocks and shoulders, and (3) the upper torso. It was found that heating intervention via e-textiles significantly improved $\Delta\overline{T}_{sk}$ and ΔTS ($p<0.05$) between CON and HEAT but the effect was insignificant for ΔMR, ΔHR and ΔCS ($p>0.05$). In the subgroup gender, heating intervention significantly improved $\Delta\overline{T}_{sk}$ in males and ΔTS in both males and females ($p<0.05$). In terms of body regions being heated, there was a significant effect on $\Delta\overline{T}_{sk}$, ΔTS and ΔCS in heating the upper torso and ΔTS in heating feet and toes ($p<0.05$). It is hoped that this study provides useful reference points for the future development of effective heating e-textiles designed with the aid of AI. For example, informing the fabrication of novel smart thermal textiles in responding different heating levels based on different genders or various target of users, such as different age groups. Thus, achieving customization in satisfying human thermal comfort by the intelligent thermal textiles.

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