



# A numerical tool for assessing human thermal safety and thermal comfort in cold-weather activities

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## Abstract

This paper describes a newly developed software tool to evaluate human thermal safety and thermal comfort in cold-weather activities aimed at guiding users to arrange activity plans and select appropriate clothing ensembles. The software inputs include conditions of activity, environment, human body, and clothing ensemble. It outputs physiological temperatures, cold injury risks, thermal sensations, and thermal comforts in intuitive ways like cloud maps and curves. The software tool is characterized by (1) integration of a thermoregulatory model that predicts human thermophysiological responses under exercise conditions in cold environments, (2) the functions of clothing ensemble database and individual parameter database, (3) the human centric outputs that directly reflect human physiological and mental status, and (4) the user-friendly operation interface and output interface, as well as a wide applicability. The software is validated with human test studies covering ambient temperatures from  $-30.6$  to  $5$  °C, clothing ensembles from 1.34 to 3.20 clo, and activity intensities from 2 to 9 Mets. The average prediction RMSEs of core temperature, mean skin temperature, thermal sensation, and thermal comfort are 0.16 °C, 0.45 °C, 0.58, and 1.41, respectively. The software is an advanced expansion to current standards and guidance of cold exposure assessment and a meaningful tool for the fields of occupational health care, cold protection, and environmental ergonomics.

**Keywords** Cold injury · Thermal comfort · Cold-weather activity · Thermoregulatory model · Clothing

## Nomenclature

$Adu$	Segment surface area ( $m^2$ )	$c$	Correction coefficient for resultant water vapor resistance and thermal insulation
$Bl$	Heat exchange: blood perfusion (W)	$cor$	Correction coefficient for resultant basal metabolic rate and blood flow
$Bl_{adj}$	Heat exchange: blood flow entering and leaving the local vessel (W)	$D$	Heat exchange: conduction (W)
$B_{AVA}$	Heat exchange: AVA blood flow (W)	$E_{mec}$	Mechanical energy generation (W)
$Cap$	Heat capacity ( $Wh \cdot ^\circ C^{-1}$ )	$E_{sk}$	Skin latent heat loss (W)
		$H$	Heat exchange: convection (W)
		$I$	Thermal insulation ( $^\circ C \cdot m^2 \cdot W^{-1}$ )
		$I_r$	Resultant thermal insulation ( $^\circ C \cdot m^2 \cdot W^{-1}$ )
		$M$	Total metabolic rate (W)
		$P$	Water vapor pressure (Pa)
		$Q$	Heat production (W)
		$Q_b$	Basal metabolic heat production (W)
		$Q_{s,sk}$	Skin sensible heat loss (W)
		$R_e$	Water vapor resistance ( $Pa \cdot m^2 \cdot W^{-1}$ )
		$R_{e,r}$	Resultant water vapor resistance ( $Pa \cdot m^2 \cdot W^{-1}$ )
		$RES$	Heat loss: respiration (W)
		$T$	Temperature ( $^\circ C$ )
		$T0$	Setpoint temperature ( $^\circ C$ )
		$t$	Time (h)
		$va$	Air speed ( $m \cdot s^{-1}$ )
		$vw$	Movement speed ( $m \cdot s^{-1}$ )

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## Greek symbols

$\eta_{net}$  Net exercise efficiency

## Subscripts

*a* Air

*ar* Artery

*cb* Central blood pool

*cr* Core

[*i*] Node number or segment number

*sk* Skin

*sve* Superficial vein

*ve* Vein

## Introduction

Cold weather is a common danger for people participating in outdoor activities or events such as high-altitude mountaineering, cross-country running, and various winter sports (Fudge 2016). Cold stress threatens human health and may lead to cold injuries such as frostbite and hypothermia (Gallea et al. 2014; Gammons et al. 2011; Haririchi et al. 2005). It is reported that the incidence of frostbite in mountaineers is 366 per 1000 individuals per year (Haririchi et al. 2005), and the incidence of frostbite and hypothermia is as high as 20% in cross-country skiing (Smith et al. 1996). Cold injuries are related to the drop of body temperature. Frostbite, the freezing injury of tissues, usually occurs when skin temperature falls below  $-0.5\text{ }^{\circ}\text{C}$  (Keatinge 1960). Hypothermia is defined as a body core temperature below  $35\text{ }^{\circ}\text{C}$ , which may cause behavior change and confusion and even threaten life (Brown et al. 2012). Selection of clothing ensembles with adequate cold-protective performance is the primary way to avoid cold injuries (Heil et al. 2016).

Thermal comfort is also critical to the participants of cold-weather activities. A comfortable experience is essential to those aiming for leisure. Also, for those joining competitive events, thermal discomfort will impact their exercise capacity and competition performance (Sandsund et al. 2012; Hébert-Losier et al. 2017). For example, cold stress and cold discomfort may influence the muscles' capability of producing power (Oksa 2002). On the other hand, hot discomfort, which usually occurs when joining intense activities with overly insulated clothing, may reduce the body's endurance performance (Maughan 2010). Thermal comfort is highly related to the body's skin and core temperatures and thermoregulatory responses (Fanger 1973; Martinez-Tellez et al. 2019). Suitable clothing ensembles should be selected according to the activity and environmental conditions to maintain the body's thermal comfort (Vanos et al. 2010).

Evaluation of thermal safety and thermal comfort is significant for cold-weather activity participants, which contributes to their clothing selection and activity arrangement to reduce cold injuries and discomfort experiences.

Currently, most evaluation methods are based on simple whole-body heat balance equations. A widely used method is the Required Clothing Insulation (IREQ) (Holmér, 1984), which is adopted by ISO 11079 (ISO 2007b). A required clothing insulation is calculated by solving the heat balance equations at given environmental and work intensity conditions. Evaluation result is given by comparing the resultant clothing insulation with the required value, and a duration limited exposure time is calculated. Another method described in the standard ASTM F2732-16 (ASTM International 2016) evaluates the comfort temperature rating at two activities levels according to a whole-body heat loss model. However, the two methods only provide evaluation results for the whole body without consideration of local body parts. Also, the primary outputs of ISO 11079 and ASTM F2732-16 are clothing insulation and temperature values, respectively. They are not direct enough for users without specialized knowledge to translate them into the results of thermal safety or thermal comfort. A recent software tool named Cold Weather Ensemble Decision Aid (CoWEDA) (Xu et al. 2021) can evaluate human thermal safety in cold environments based on a multisegment human thermoregulatory model (Xu and Werner 1997; Xu et al. 2005). It outputs both the whole-body and local evaluation results in terms of endurance time to hypothermia and frostbite. As a successful tool targeted at end users, CoWEDA provides several critical endurance time values as outputs. But some users with specialized knowledge may also require to obtain the underlying physiological data as well as detailed evaluation results concerning injury level and thermal comfort. A tool that can support diverse user communities including ordinary people and specialized researchers can further serve the fields of biometeorology and ergonomics.

The objective of this paper is to develop a software tool that addresses the evaluation of thermal safety and thermal comfort of people in cold-weather activities. The presented work includes (1) development of an evaluation method based on a thermoregulatory model that simulates thermophysiological responses of people participating in cold-weather activities and (2) development of a user-friendly software application that enables users to operate easily and presents the results comprehensively and intuitively.

## Methods

THE presented tool integrates a thermoregulatory model, databases of clothing ensembles and individual parameters, and criteria of thermal safety and thermal comfort into a user-friendly software application. The flow chart of the tool is shown in Fig. 1. The software inputs include activity information, environmental conditions, clothing

ensemble, and individual parameters. The clothing ensemble parameters including thermal insulation and water vapor resistance, and the individual parameters including age, gender, body height, and weight, can be selected from the database or predefined by the users. Then, the calculation process is based on the solution of the thermoregulatory model, which can be either solved independently or interactively run with a Computational Fluid Dynamics (CFD) software addressing the heat exchange between human body and environment. The software outputs include physiological temperatures and evaluation results of thermal safety, thermal sensation, and thermal comfort in forms of cloud maps, curves, and reports.

The software was developed using Java and JavaScript language and deployed on a server with CentOS 7 system. A browser/server structure is adopted.

### Thermoregulatory model

A recent thermoregulatory model for predicting thermo-physiological responses of people in cold-weather activities (Chen et al. 2022a) is used in the presented software. The inputs of the model include the parameters of activity, environment, clothing, and human body, which will be shown in detail in the section of software inputs. The outputs of the model include thermophysiological responses such as core temperature and skin temperature.

The model divides human body into 20 segments: face, head, chest, stomach, shoulder, back, upper arms (×2), forearms (×2), hands (×2), hips (×2), thighs (×2), calves (×2), and feet (×2). Each segment is further divided into 4 layers (nodes): core, artery, vein, and skin. In addition, limb segments have superficial vein nodes for the accuracy of local skin temperature prediction. A center blood pool is located in the

chest. Arteriovenous anastomosis (AVA) blood flow exists in the hands and feet, which connects superficial veins and arteries. Figure 2 shows the model’s body construction scheme. The model is based on the heat balance equations of the nodes:

$$Cap_{cr[i]} \frac{dT_{cr[i]}}{dt} = Q_{cr[i]} - D_{cr-sk[i]} + Bl_{cr[i]} + H_{ar-cr[i]} + H_{ve-cr[i]} - RES_{[i]} \tag{1}$$

$$Cap_{sk[i]} \frac{dT_{sk[i]}}{dt} = Q_{sk[i]} + D_{cr-sk[i]} + Bl_{sk[i]} + H_{sve-sk[i]} - Q_{s_{sk}[i]} - E_{sk[i]} \tag{2}$$

$$Cap_{ar[i]} \frac{dT_{ar[i]}}{dt} = Bl_{adj,ar} - H_{ar-cr[i]} - H_{ar-ve[i]} \tag{3}$$

$$Cap_{ve[i]} \frac{dT_{ve[i]}}{dt} = Bl_{adj,ve} + Bl_{cr-ve[i]} + Bl_{sk-ve[i]} - H_{ve-cr[i]} + H_{ar-ve[i]} \tag{4}$$

$$Cap_{sve[i]} \frac{dT_{sve[i]}}{dt} = Bl_{adj,sve} + Bl_{AVA[i]} + Bl_{sk-sve[i]} - H_{sve-sk[i]} \tag{5}$$

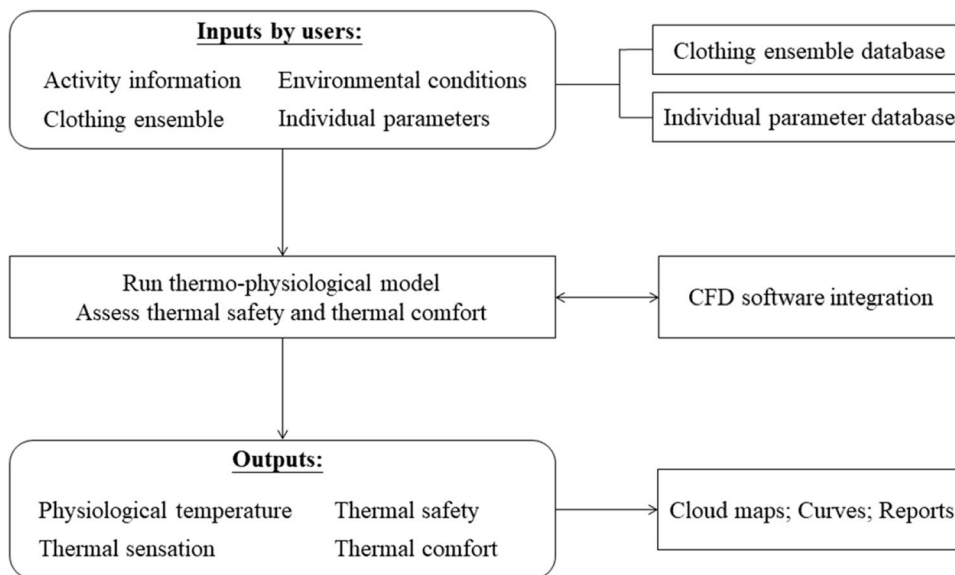
$$Cap_{cb} \frac{dT_{cb}}{dt} = Bl_{adj,cb} \tag{6}$$

$Q_{s_{sk}}$  and  $E_{sk}$  are sensible and latent heat losses from the skin, respectively, which are influenced by clothing insulation and evaporative resistance:

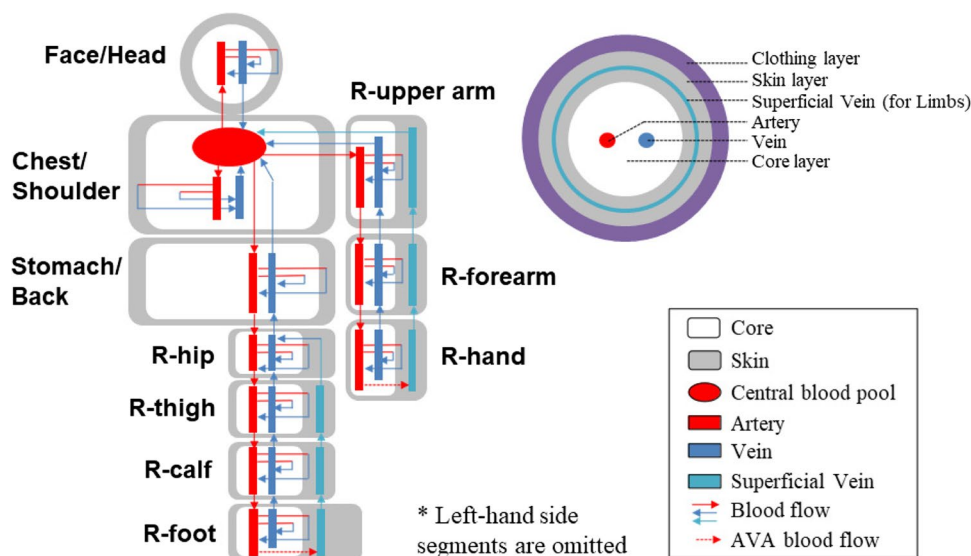
$$Q_{s_{sk}} = Adu_{[i]} \cdot \frac{T_{sk[i]} - T_{a[i]}}{I_{[i]}} \tag{7}$$

$$E_{sk} = Adu_{[i]} \cdot \frac{P_{sk[i]} - P_{a[i]}}{R_{e[i]}} \tag{8}$$

Fig. 1 Flow chart of the software tool



**Fig. 2** Body construction scheme of the thermoregulatory model



In particular,  $I$  and  $R_e$  are impacted by ambient wind and clothing pumping effect in cold-weather activities, as is described by ISO 9920 (ISO 2007a):

$$I_r = c \cdot I & R_{e,r} = (0.3 - 0.5c + 1.2c^2) \cdot R_e \tag{9}$$

where  $I_r$  and  $R_{e,r}$  are resultant clothing total insulation and evaporative resistance.  $c$  is a correction coefficient calculated by air speed  $v_a$  and human movement speed  $v_w$ :

$$c = e^{-0.281 \cdot (v_a - 0.15) + 0.044 \cdot (v_a - 0.15)^2 - 0.492 v_w + 0.176 v_w^2} \tag{10}$$

In addition, in actual situations, activities affect clothing insulation and heat transfer via local limb movements. Given that the current model is a general model without considering the heterogeneity among body segments, this effect is not particularly considered in the current work since limb movements vary a lot between different activity types. It is valuable to consider this to improve the model’s accuracy for specific situations in the future.

The detailed control equations, physiological parameters, and model validation were described by Chen et al. (2022a).

The model is characterized by particular consideration of people participating in cold-weather activities. The model uses net exercise efficiency to calculate metabolic heat production during exercise and considers the low temperature effect on basal metabolic rate and basal blood flow rate (Chen et al. 2022a). Net exercise efficiency describes the percentage of mechanical energy production to nonbasal metabolic energy (Brooks 2011):

$$\eta_{net} = \frac{E_{mec}}{M - Q_b} \tag{11}$$

where  $\eta_{net}$  is the net exercise efficiency,  $M$  is the total metabolic energy production,  $Q_b$  is the basal metabolic heat production, and  $E_{mec}$  is the mechanical energy generation. Thus, the metabolic heat production  $Q$  during exercise is calculated by (Chen et al. 2022a):

$$Q = M - \eta_{net} \cdot (M - Q_b) \tag{12}$$

The model considers that basal metabolic rate and basal blood flow rate were found to be influenced by the tissue temperature (Werner and Buse 1988), and the effect will be significant during long-term cold exposure. The effect depends on the difference between tissue temperature and its setpoint temperature, described by a correction coefficient (Werner and Buse 1988):

$$cor = 2^{(T - T_0)/10} \tag{13}$$

where  $cor$  is the correction coefficient,  $T$  is the tissue temperature, and  $T_0$  is the corresponding setpoint temperature. In this model, the real basal metabolic rate and basal blood flow rate are calculated by multiplying the thermoneutral value by the correction coefficient (Chen et al. 2022a).

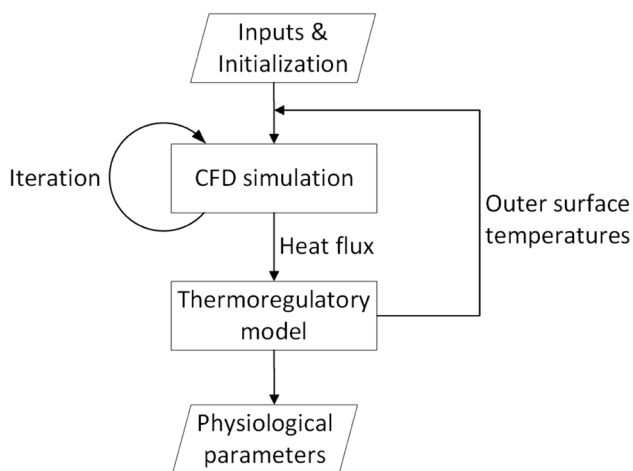
The model is able to consider the diversity of the population participating in cold-weather activities. The thermoregulatory control equations of the model consider the individual characteristics such as gender, age, height, and weight, which are based on the JOS3 model (Takahashi et al. 2021), an advanced thermoregulatory model addressing the individual effects on thermoregulatory responses.

The model can be run independently to predict thermo-physiological responses, while a method coupling the model with a CFD simulation of body-environment heat exchange (Yang et al. 2017) is provided as

an option in the software. When the thermoregulatory model is used independently, it calculates body's sensible heat loss considering the thermal insulation of the clothing and the temperature difference between the skin and ambient environment, as shown in Eq. (7). When coupling with a CFD calculation, the body's sensible heat loss is given by CFD simulation, which takes the body's geometry into account to calculate the thermal field around body.

A CFD computational thermal manikin was obtained by 3D scanning of the thermal manikin "Newton" in a standing position and was subdivided into 20 segments corresponding to the thermoregulatory model. The process of coupling calculation of the thermoregulatory model and CFD simulation is shown in Fig. 3. During each time interval, the thermoregulatory model calculates the thermophysiological responses and passes the outer surface temperatures of the body segments (skin temperatures for naked segments and outer clothing temperatures for clothed segments) to CFD simulation, which are used as the boundary condition of the CFD numerical manikin. Then, CFD simulation is conducted to simulate the sensible heat flux between the body and environment, which is the feedback to the thermoregulatory model for the next interval. The details and validation of the coupling calculation method were described by Yang et al. (2017).

The commercial CFD software Fluent 18.0 is used for CFD simulation, and the thermoregulatory model is developed with MATLAB R2020a, where "ode15s" method is used to solve the model with  $1 \times 10^{-5}$  relative error tolerance. A Shell script is programmed in the software to implement the automatic interactive calculation between the thermoregulatory model and CFD simulation.



**Fig. 3** Process diagram of the coupling calculation method

## Software inputs

The software homepage displays four modules to the users after logging in, including "Calculation," "Individual Database," "Clothing Database," and "Model Database." Users can start a new calculation task by entering "Calculation" module. The other three modules are used to manage the individual parameter database, clothing ensemble database, and thermoregulatory model versions, respectively.

After entering the "Calculation" module, a user-friendly interface is provided to guide inputs in the sequence of task information, activity and environment, body and clothing, and task submission. Firstly, users define the name and description of the calculation task in the "task information" section. Then, users input activity and environmental parameters in "activity and environment" section, where a basal setting page and an advanced setting page are provided. In the basal setting page, users select activity information in three drop-down boxes, including activity type (recreation, sports, and others), activity name, and activity level (low, middle, high, and competitive intensity). The activity information is converted into corresponding metabolic rate (Mets) and net exercise efficiency ( $\eta_{net}$ , %) at the background of the software as the direct inputs of the thermoregulatory model. Ainsworth et al. (2011) gave the metabolic rates of different activities at different intensity levels. Böning et al. (2017) and Cavagna and Kaneko (1977) gave the  $\eta_{net}$  of different activities. Some common activities and their corresponding metabolic rates and  $\eta_{net}$  values adopted in the software are listed in Table 1. Also, the users input environmental parameters including air temperature, radiation temperature, air speed, and relative humidity. Meanwhile, the advanced setting page is provided for users with professional knowledge or research demands. Users can input manually the metabolic rate and net exercise efficiency values, and they are enabled to create a series of successive exposure phases with different input parameters, which increases the usability and flexibility of the software.

In the "Body and Clothing" section, users select clothing ensemble and individual model via drop-down boxes, from the clothing ensemble database and individual parameter database of the software. An advanced setting page is provided to select specific local protective equipment for face/head, hands, and feet.

The clothing database integrates various typical cold-weather clothing ensembles, including sportswears, occupational suits, and local protective gears. Their physical parameters, mainly including thermal insulation and evaporative resistance, were measured by a thermal manikin or referred to previous literatures and handbooks. Besides, users can create new clothing ensemble items according to their requirements by inputting the clothing ensemble's parameters including its name, type, weight, total thermal



**Table 1** Activities and corresponding metabolic rates and net exercise efficiencies (Ainsworth et al. 2011; Böning et al. 2017; Cavagna and Kaneko 1977)

Activity	Intensity	Mets	$\eta_{net}(\%)$
Rest	/	1.3	0
Walking	Low	2.5	30
	Moderate	3.5	35
	High	4.3	40
Running	Low	6.0	40
	Moderate	8.3	45
	High	10.5	50
	Competitive	12.3	50
Mountaineering	/	8	30
Cross-country skiing	Low	6.8	21
	Moderate	9.0	21
	High	12.5	21
	Competitive	15.0	21
Skating	Low	5.5	15
	Moderate	7.0	15
	High	9.0	15
	Competitive	13.3	15
Occupational operation	Low	2.5	20
	Moderate	4.3	20
	High	7.0	20

insulation, total evaporative resistance, moisture permeability, and air permeability. Users can also choose to input local thermal insulations and local evaporative resistances by segments corresponding to the thermoregulatory model.

A series of human body types are predefined in the individual parameter database, which are the combinations of gender, age, and BMI level referring to WHO’s BMI division, as listed in Table 2. The individual parameters include name, BMI level, BMI, age, gender, height, weight, bust, waistline, and hipline. Users can create new individual data if needed. Also, users can change individual parameters directly in the “Body and Clothing” input section. The current software takes age, gender, height, and weight as key parameters influencing model prediction, which directly

influence the calculation of surface area, metabolic rate and thermoregulation responses, as was described and validated by the JOS-3 model (Takahashi et al. 2021).

In the last input section “Task submission,” users set the exposure time and time interval of the output data. Advanced settings are provided for users to select a thermoregulatory model version and turn on the interactive calculation with CFD. Then, users submit the calculation task to the server and wait for the results.

### Software outputs

The outputs of the software include physiological data and evaluation results of thermal safety, thermal sensation, and thermal comfort. A comprehensive and intuitive output interface is developed. The software displays the results by human-body cloud maps and curves. Cloud maps are used to display local results by segment, including local skin temperatures, local cold injury risks, local thermal sensations, and local thermal comforts. Curves are used to display whole-body values changing over time, including mean skin temperature, core temperature, and sweating amount. Also, the final evaluation results of hypothermia risk, overall thermal sensation, and overall thermal comfort are displayed. Users can download an evaluation report containing the summarization and results of the calculation task. Detailed data can also be exported as CSV files.

The evaluation criteria or calculation methods of the results are described below.

The physiological data including skin temperature, core temperature, and sweating are the results predicted by the thermoregulatory model. Mean skin temperature is the average value of local skin temperatures weighted by surface areas of the segments. Core temperature is the temperature of core layer of stomach.

The evaluation of thermal safety includes the risk of local cold injuries and hypothermia. Local cold injuries are mainly caused by low skin temperature, including nonfreezing injury like frostnip and freezing injury known as frostbite (Cappaert et al. 2008). In the current software, nonfreezing injury risk is considered when local skin temperature

**Table 2** Human body types predefined in the software

		BMI level					
		Underweight		Normal weight		Overweight	
		Male	Female	Male	Female	Male	Female
Age	Teenager	Age = 15	Age = 15	Age = 15	Age = 15	Age = 15	Age = 15
		BMI = 17	BMI = 17	BMI = 20	BMI = 20	BMI = 26	BMI = 26
	Adult	Age = 24	Age = 24	Age = 24	Age = 24	Age = 24	Age = 24
BMI = 17		BMI = 17	BMI = 20	BMI = 20	BMI = 26	BMI = 26	
Elderly	Age = 60	Age = 60	Age = 60	Age = 60	Age = 60	Age = 60	
	BMI = 17	BMI = 17	BMI = 20	BMI = 20	BMI = 26	BMI = 26	

is lower than 5 °C, and freezing injury occurs when local skin temperature falls to −0.5 °C or lower (Cappaert et al. 2008). Hypothermia is caused by low core temperature and is divided into three levels, including mild, moderate, and severe hypothermia corresponding to core temperature lower than 35 °C, 32 °C, and 28 °C (Fudge 2016).

The UC Berkeley (UCB) model developed by Zhang et al. (2004) is adopted in the software to evaluate thermal sensation and thermal comfort, which is capable of predicting both local and overall thermal sensation/comfort in transient nonuniform environments. Thermal sensation is divided into 7 levels as the integers from −3 to 3, representing “very cold,” “cold,” “cool,” “neutral,” “warm,” “hot,” and “very hot,” respectively. Thermal comfort is divided into 9 levels as the integers from −4 to 4, representing “unacceptable,” “very uncomfortable,” “uncomfortable,” “slightly uncomfortable,” “just comfortable,” “slightly comfortable,” “comfortable,” “very comfortable,” and “very satisfied,” respectively. The local thermal sensation is predicted by a logistic function of local skin temperature, considering the effects of local skin temperature, mean skin temperature, and change rates of skin and core temperatures, and the overall thermal sensation is a weighted average of local values (Zhang et al. 2004). In addition, a thermal sensation prediction method based on UCB model particularly applied for the Chinese people (Zhou et al. 2014) is also integrated in the software, which corrected the model parameters according to the field studies conducted with Chinese population. Users can select the thermal sensation model when submitting the calculation tasks, which helps the software to further consider individual differences. The local thermal comfort is calculated by corresponding local thermal sensation and overall thermal sensation, and the overall thermal comfort is determined by local thermal comfort according to the rules described by Zhang (2003).

## Results and discussion

### Validation with human studies

Three human studies covering various activity intensities in cold environments are used to validate the presented software tool. The contents of the studies are listed in Table 3.

The measured core temperature, mean skin temperature, hand skin temperature, body thermal sensation, and thermal comfort were compared with those predicted by the software tool. The CFD–thermoregulatory model coupling method was used to simulate study 1, and thermoregulatory model-based calculation was used for study 2 and 3. Root mean square error (RMSE) was used to determine the goodness of fit between the predicted and experimental results, which is defined by

**Table 3** Contents of human studies used to validate the presented software

Source	Subjects		Age	Height (m)	Weight (kg)	Time (min)	Temperature (°C)	Air speed (m/s)	RH (%)	Clothing insulation (clo)	Intensity (Mets)
	Number-gender	Weight									
Study 1 (Gao et al. 2015)	9	males	24	1.81	74.5	0–90	3.4	0.4	50	2.28	2
Study 2 (a) (Gavhed and Holmer 1996)	10	males	28	1.83	71.2	0–90	−30.6	0.2	100	2.35, 2.59, 3.12, 3.20, separately	4
						90–120	22				4.1
Study 2 (b) (Gavhed and Holmer 1996)	10	males	28	1.83	71.2	120–165	−10	0.2	100	3.12, 3.20, separately	Rest
						50–110	−10				4.1
Study 3 (Chen et al. 2022b)	6	males	25	1.74	71.2	0–10	5, 0, −5, −10, separately	0.2	60–70	1.34	2.4
						10–30					9.0
						30–40					2.4
						40–60					6.1

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2} \quad (14)$$

where  $e_i$  is the error between predicted and observed values at  $i$  th timepoint and  $n$  is the number of timepoints. The prediction can be considered valid if the RMSE is less than the standard deviation (SD) of the observed data.

Figure 4a–e shows the comparison of predicted and experimental results. For study 1 which lasted 90 min, the data at 30, 60, and 90 min were selected to be displayed in the comparison figures. For studies 2 and 3, the data at the end of each experimental phase (i.e., the change point of activity or environmental conditions) were used in the comparison figures. On the whole, the figures reflect the validation results for various exposure time lengths from 10 to 165 min, as well as a number of ambient temperature conditions from  $-30.6$  to  $5$  °C and various activity intensities from 2 to 9 Mets. Most experimental data points are presented with their SD bars, except those not provided with SD values in the original literature.

Figure 4a shows the validation results of core temperatures. 23 of 28 predicted core temperatures are within the range of observed values  $\pm$  SD (data without SD are not counted, the same below). The RMSE for predicted core temperatures is  $0.16$  °C, while the average SD is  $0.22$  °C.

Figure 4b shows the validation results of mean skin temperatures. 27 of 32 predicted skin temperatures fall in the observed SD range. The RMSE is  $0.45$  °C, smaller than the average SD of  $0.61$  °C.

Figure 4c compares the results of hand skin temperatures. Hands are one of the most vulnerable segments to cold injuries like frostbite, whose temperatures can be much different with those of torso (Tanaka et al. 1983). Thus, hand skin temperature is particularly compared to validate the software's prediction performance of local parts. Data from studies 1 and 3 are used, since study 2 did not report the hand skin temperatures. As shown in Fig. 4c, 12 of 16 predicted hand skin temperatures are within the range of observed values  $\pm$  SD. Also, the RMSE for predicted hand skin temperatures is  $1.89$  °C, falling into the range of average SD,  $1.93$  °C.

Figure 4d compares the predicted and measured body thermal sensations. In study 1 and study 3, a 9-level thermal sensation rating system ( $-4$  to  $4$ ) was adopted, while the presented software as well as study 2 adopted a 7-level rating system ( $-3$  to  $3$ ), as described in the "Software outputs" section. To compare the thermal sensation results under a unified rating rule, the sensation ratings measured with 9-level system were transformed to 7-level system by multiplying them by  $3/4$ . The corresponding SD values were also multiplied by  $3/4$ . Figure 4d shows that 21 of 28 predicted body thermal sensation values are within the

range of corresponding SD. The RMSE of thermal sensation prediction is  $0.58$ , and the average SD is  $0.83$ .

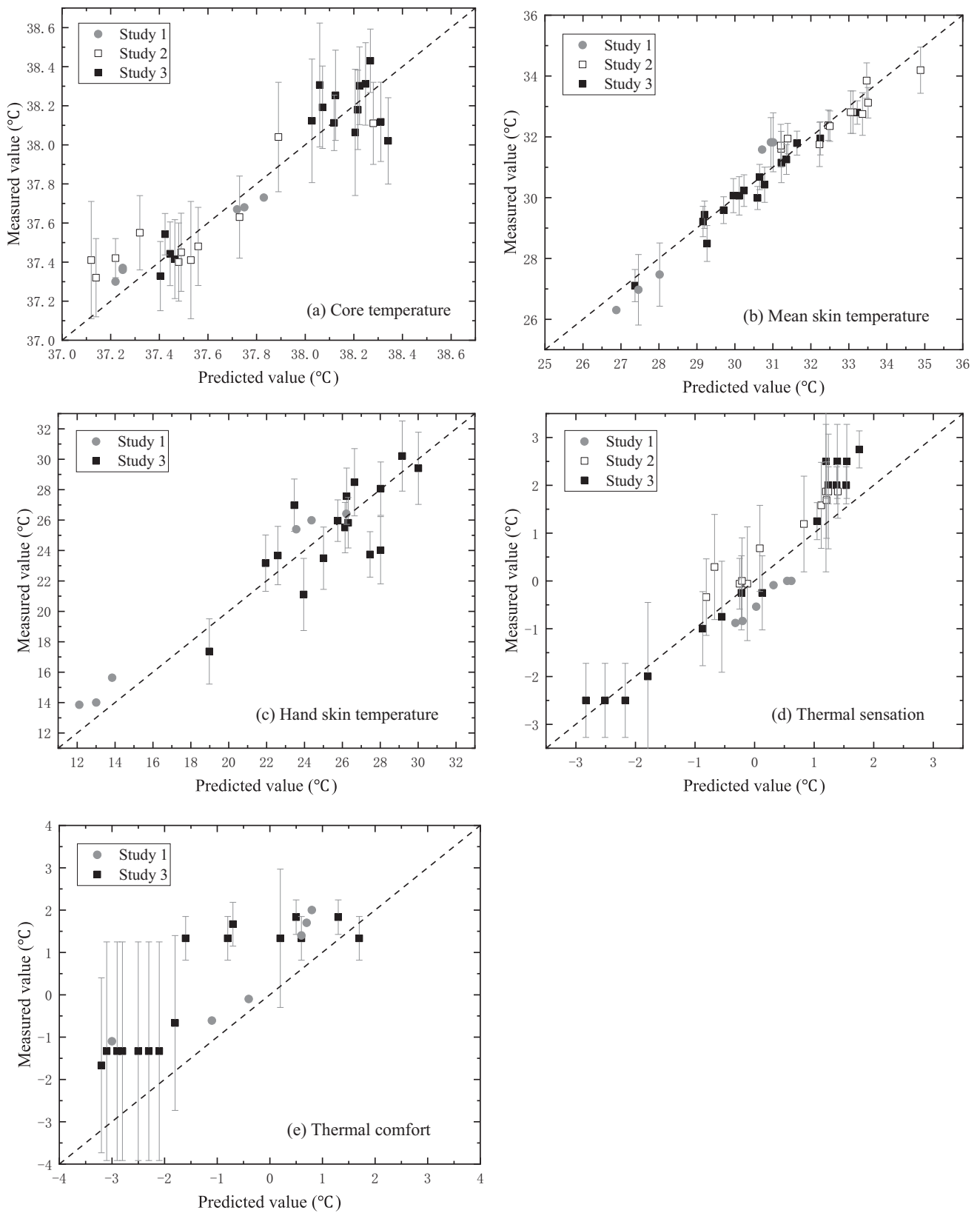
Figure 4e shows the validation results of body thermal comforts. Data from studies 1 and 3 are used, since study 2 did not report thermal comfort. In study 1, a 4-level thermal comfort rating system was used (0: comfort; 1: slightly uncomfortable; 2: uncomfortable; and 3: very uncomfortable), where lower rating represents higher comfort level. However, the presented software and study 3 adopted a 9-level thermal comfort rating system ( $-4$  to  $4$ ), where higher rating represents higher comfort level. A transformation method between the two rating rules is established by comparing the ratings' semantics in the two rating systems, which is described as follows in the form of "4-level rating number  $\sim$  9-level rating number (meaning)":  $0 \sim 2$  (comfortable);  $1 \sim -1$  (slightly uncomfortable);  $2 \sim -2$  (uncomfortable); and  $3 \sim -3$  (very uncomfortable). Transformation of noninteger rating results is based on linear interpolation. Based on such a transformation rule, the predicted and measured results of thermal comfort are compared under the 9-level system. As shown in Fig. 4e, 10 of 16 predicted body thermal comforts are within the SD range. The RMSE of thermal comfort prediction is  $1.41$ , smaller than the average SD of  $1.54$ . Interestingly, Fig. 4e shows that most of the predicted results are lower than corresponding measured results. The bias may be explained that the software uses Zhang's model (2003) to predict thermal comfort, where the overall thermal comfort was considered mainly determined by the two minimum local comfort votes. But for people taking activities, the thermal comfort acceptable range was found to be much greater than resting ones (Lin et al. 2022), different with the statistical cases like Zhang's experiment (2003). Thus, the software slightly underestimates the thermal comfort level in those activity situations. A more accurate thermal comfort model for cold-weather activity participants is needed to improve the software's prediction performance. But the current prediction results are still acceptable given that thermal comfort is quite subjective and varies a lot between individuals.

The RMSE values of predicted core temperature, mean skin temperature, hand skin temperature, body thermal sensation, and thermal comfort are reasonable and all within the range of measured values  $\pm$  SD, which indicates the validity of the presented software tool.

## Discussion

The presented software is a knowledge-based tool to evaluate human thermal safety and thermal comfort in cold-weather activities. The software is human centric to provide results easy to understand and use. It is an advanced





**Fig. 4** Comparison of measured and predicted values. (a) core temperature, (b) mean skin temperature, (c) hand skin temperature, (d) thermal sensation, and (e) thermal comfort

expansion to current cold-weather and cold stress management tools. The software comprehensively considers people's safety and comfort requirements in cold-weather activities and is designed for a variety of users such as participants of outdoor activities, clothing designers, and researchers.

The software is a human centric tool with the ultimate aim to ensure human safety and optimal human performance during cold-weather activities. Cold stress impairs human physical abilities, and cold injuries threaten human health and even life. People need a guidance to arrange their activity plans and select appropriate clothing ensembles to keep safe and ensure a good activity experience. The software outputs a series of quantitative measures to assess human thermal safety and thermal comfort in given situations. In previous work, Holmér (1984) and ISO 11079 (ISO 2007b) defined a method IREQ to predict required thermal insulation to maintain body thermal balance, as well as duration limited exposure and a required recovery time. But the direct evaluation target concentrates on clothing ensembles, which is not intuitive enough for the general population joining cold-weather activities. Also, local cooling and local cold injuries are not considered in IREQ, which are very common and widely recognized in various situations such as military operations (O'Donnell et al. 2017), exercise (Sullivan-Kwantes et al. 2017), and rescue operations ((Kupper et al. 2003). Local protection is as critical as the overall cold injury protection. The presented software and its evaluation methods can give more comprehensive outcomes than current standards to address the complex requirements of thermophysiological assessment of cold-weather activity participants. The software's outputs concentrate on human physiological status, which are easy to understand and to be applied in practical situations.

The software is an advanced supplement to existing guidance of cold injury management. One of the common cold injury guidance is wind chill index (WCI) (Siple 1945) and its updated version, wind chill equivalent temperature (WCET) (Rintamäki 2004), which address the assessment of frostbite risk. WCET presents frostbite risk as a look-up table, where frostbite times depend on ambient air temperature and air velocity. A more recent index, Universal Thermal Climate Index (UTCI) (Jendritzky et al. 2012), presents equivalent temperature according to air temperature, relative humidity, and air speed. However, the actual frostbite risk of human body also depends on local thermal protection, activity level, and physiological responses such as vasomotion (Brajkovic and Ducharme 2006). Also, frostbite risk differs with segments. The presented software is a useful tool to provide more comprehensive assessment of frostbite risk by considering these non-environmental factors compared with WCET. Furthermore, the software

considers severity division of cold injuries, which is not directly provided in existing guidance. Also, the software helps to educate users about cold weather dangers and improve their awareness of thermal safety by translating cold-weather activity information into thermophysiological outcomes and safety consequences. As is suggested by researchers, improving awareness is critical to cold injury protection of the public (Imray and Oakley 2005; Mäkinen and Hassi 2009).

The software is a useful tool comprehensively considering the requirements of people joining cold-weather activities. The target of existing software tools like CoWEDA (Xu et al. 2021) is limited to evaluating human thermal safety in cold exposures, which mainly concentrates on occupational situations like military operation and rescue. But thermal safety problems are also common in recreational situations (Procter et al. 2018), where people also value their thermal comfort. As for competitive activities, people usually select appropriate clothing ensemble to ensure thermal comfort for better physiological performance (Sjödin et al. 1996); thus, it is not enough to only consider cold protection of them. The presented software provides comprehensive and intuitive evaluation outcomes of human thermal safety and comfort, which helps the users to select appropriate activity environments and clothing ensembles according to their personal requirements. Also, the cold stress management tools such as IREQ and CoWEDA are mainly applied to consider human thermophysiological stress at the cold-side. But heat stress is also common in cold-weather activities caused by excess clothing insulation or high activity intensities (Rintamäki and Rissanen 2006). The presented software adopts a thermoregulatory model that is able to predict thermophysiological responses in various activity intensity levels. The use of net exercise efficiency helps to enhance the model's prediction performance in high intensity conditions (Chen et al. 2022a). The software is validated with measured data covering intensities from 2 to 9 Mets and is able to give accurate thermal sensation and comfort predictions in both cold-side and hot-side.

The software tool is user-friendly and can meet the requirements of different user communities. The software integrates the specialized knowledge in the fields of thermophysiological simulation, thermal comfort prediction, exercise physiology, and medicine into a tool with user-friendly operation interface and guidance and provides human centric evaluation results. General users without relevant knowledge backgrounds can easily get started and understand the results. For users with specialized requirements like research, the software provides a number of advanced functions in advanced settings. The software also outputs all the physiological data during the calculation process, which can be exported for further research. Furthermore, the software can be easily adapted or extended. The thermoregulatory

model, clothing ensemble database, individual parameter database, and evaluation criteria can be managed and customized by users with different purposes. Thus, the presented software is a powerful tool to support various user communities such as outdoor activity participants, clothing designers, event organizers, government administrators, and researchers.

The limitation of this study is the size of validation data, whose conditions are not extreme enough to reflect high level cold or heat stress. More experimental data in conditions with lower temperatures, higher wind speeds, and higher activity intensities will be gathered in the future to further validate the presented software. Also, the software outputs are limited to evaluation results at present, without warnings or suggestions for the users. Future work will consider to provide more information in the outputs, such as endurance time to cold injury and suggestions on clothing selection. In addition, the current used thermoregulatory model does not consider the detailed extremity parts such as fingers and toes. Modelling work with more detailed segment division will be considered in the future.

## Conclusions

A software tool is developed to evaluate human thermal safety and thermal comfort in cold-weather activities. It is aimed at guiding users to arrange activity plans and select clothing ensembles appropriately to ensure their health, experience quality and activity performance. A thermoregulatory model for cold-weather activities, databases of clothing ensemble and individual parameters, and criteria of thermal safety and comfort evaluation are integrated into the developed tool. The prediction performance of the software on physiological and mental responses is validated by a variety of human test data. The software concentrates on human thermophysiological status and provides human centric evaluation results. It is a supplement and expansion to current cold exposure management tools. The software comprehensively evaluates cold injury risk and thermal comfort, which is capable of calculating both cold-side and hot-side conditions. It is user-friendly and can be applied to various user groups. The software is a meaningful tool for the fields of occupational health care, cold protection, and environmental ergonomics.

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