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REVIEW **OPEN ACCESS**

MODELS FOR QUANTIFYING HUMAN THERMOREGULATORY RESPONSES

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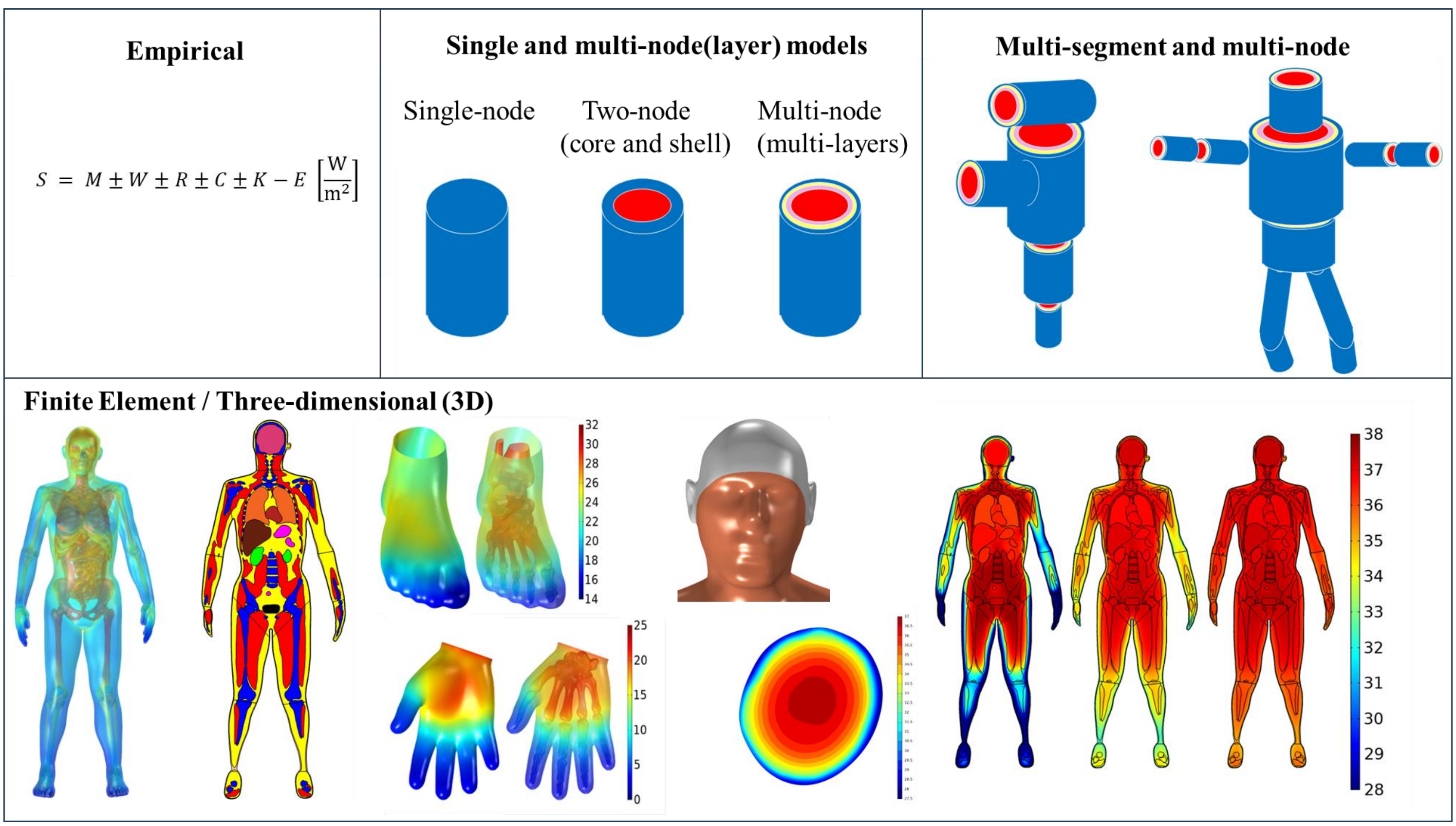
ABSTRACT: This review examines the evolution of thermal models applicable to water immersion and outlines the fundamental principles of accessible human thermoregulation and physiological models. It identifies available source code and proposes future development steps to enhance model generalizability. These models are crucial for translating biophysical and physiological data into practical applications, extrapolating quantitative relationships to novel conditions, and identifying knowledge gaps to guide future research and model refinement.

Figure 1. Graphical outline examples of major categories of modeling types (1-4)



Keywords: thermal modeling, biophysics, immersion, hypothermia

BACKGROUND – SUMMARY

The majority of models reviewed fall into four broad categories: 1) empirical (i.e., non-dimensional, mathematical or statistical models), 2) node models (single or multiple layers), 3) multi-segmental, and 4) finite element or three-dimensional (3D) models (1-4). Each of these uses empirical (mathematical/statistical), rational (mechanistic), or hybrid (combination of empirical and rational) methods for developing their 'inner workings'. Segmental biophysical models such as the five-six cylinder model have developed from Stolwijk and Hardy, Werner and Webb, to Xu models (5-9), and underpin the basis of the Cold Weather Ensemble Decision Aid (CoWEDA) and Probability of Survival Decision Aid (PSDA) applications (10-15). Multi-node engineering models such as Montgomery, Yermakova, and Wissler (2, 16-23) have been widely applied to generate guidance or evaluation of varied exposure conditions and provide the basis for other modeling methods. Simplified modeling approaches based on empirically predictive methods such as Givoni and Goldman (24-27) or from mechanistic methods (e.g., Kraning and Gonzalez (28-31)) used to predict responses to metabolic heat production, clothing, and environment have formed the basis for widely used heat stress models (e.g., the Heat Strain Decision Aid (HSDA) (32-38), SCENARIO (28, 30, 31, 39, 40)). More comprehensive and computationally complex methods such as finite element models (3, 4, 41-43) provide helpful advancements to the scientific field. Each strategy has advantages but ultimately, with much more data, empirically based models will help to revalidate fundamental relationships and possibly identify previously overlooked quantitative rules. Other models such as the highly cited Fiala models (44, 45), mainly focused on comfort, are used in the design of climate controlled buildings.

This review highlights a variety of existing models that have been usefully applied to predicted stay time in cold water, survival decision tools, and mission preparation (e.g., appropriate protective clothing ensembles, work pacing, etc.). Further development of the models will shift from group/average predictions to more precise personalized predictions. It is apparent that immersion cold modeling has been driven almost exclusively by military needs. There is no predictive model that is fully adequate for the prediction of core temperature, extremity temperatures and function, and metabolic limits (mental and physical endurance limits) for diving and cold water swimming.

INTRODUCTION

The ability to quantitatively model human thermoregulatory and physiological responses to environmental exposures and activities is of keen interest to many groups across the public, private, and military sectors. This ability provides a more informed risk mitigation for both the public and private sectors, through better information sharing and safety planning to reduce injuries and performance decrements associated with environmental exposures. Typically for civilian activities, guidance related to exposures consists of levels of avoidance to exposure (e.g., guidance on when to wear more or less clothing, or when to completely avoid being outside). This is also true for workplace exposure standards (46). However, for military activities the guidance is typically based on how best to protect from the environmental stressors, as there is an assumption that the exposure will happen (i.e., avoidance is not a typical operational option). Additionally, in civilian settings, the ability to remove oneself from exposure is often more feasible (e.g., go inside), while in military operations exposure is often more complicated and protracted.

Over the years, a number of mathematical models have been developed for use in specific conditions (a specific model for heat stress, another model for cold exposure, another for diving, etc.). While this approach has worked well for many years and has provided helpful insights to users and their intended use cases, there is an increasing interest in the ability to model more dynamic activities and exposures. For example, several models developed have been extensively validated to steady-state activities in hot, cold, or during immersion exposures. However, few models have the versatility to describe dynamic activities (e.g., work, rest, work) or more complex conditions (e.g., walking on land, immersed in water, then walking again; or swimming, cycling, and running in a triathlon). Several published efforts have shown this ability within the models themselves (34, 40); however, it often requires a subject matter expert to make them work effectively.

Biomedical modelers have worked extensively to provide accurate and comprehensive methods capable of addressing responses to a large spectrum of user interests. However, these methods have become complex and difficult to use by a non-modeling expert, in part, because of ad hoc nature of the modifications and additions that result in models that only the well-informed expert physiological modelers can decipher. Therefore, the ultimate objective of this work is to provide a tool(s) that can be comprehensive in nature but designed with user friendly and intuitive use interfaces. In other words, a well validated “turnkey” system that doesn’t require the original developer to operate.

This review describes the mathematical basis of models, providing background on the necessary inputs and how those are typically managed computationally. The review then provides a chronology of the development of biophysical models. It concludes with a brief discussion about current “state of the models” with the most commonly used models and their applications. In the chronology, further information is provided about the availability of source code and methods that are openly available (published in peer- reviewed journals, technical reports). This outline provides a platform for future work to use and compare these models/methods in various conditions with the goal of combining, refining, or selecting of appropriate methods in the development of a comprehensive approach. The ultimate goal of further research in this area is to develop generalized models that can predict outcomes for conditions that have not even been previously encountered, using inputs and producing outputs that are relevant and valid for military applications.

METHODS

A literature review was conducted by a subject matter expert specifically to evaluate human thermoregulatory models that included published, reproducible or functional code or models that have functioning versions obtained for the purposes of this work (search sources included: Google Scholar, PubMed, Defense Technical Information Center, and other internal records). Model selection included those with published analyses related to the prediction of core body temperature (Tc) or thermal health risks at a minimum; while ideally models included additional physiological predictions (e.g., skin temperature (Tsk), muscle temperature (Tm), cardiac output, shivering, sweating). An additional consideration was for models that have shown clear applicability to militarily relevant working conditions (e.g., extreme hot, cold, immersion, high intensity).

RESULTS

What is required for a comprehensive model of human thermoregulation?

Typically, this approach requires knowledge of human physiology and metabolism, biophysics, heat transfer, environmental science, mathematics, and possibly programming.

The major models reviewed fall into four broad structural categories. We see these as 1) empirical (i.e., non-dimensional, mathematical or statistical models), 2) node models (single or multiple layers), 3) multi-segmental, and 4) finite element or three-dimensional (3D) models (Figure 1 shown above).

Within these categories of modeling types, there are three categories for modeling design approach: 1) empirical (i.e., statistically created, data-driven), 2) rational (mechanistic), or 3) a combination of both (i.e., a hybrid). Models of human thermoregulation include a representation of the human body and physiology (e.g., sex, size, health status). The human representation within the model is often quantified into body segments, tissue types (fat, muscle, bone), blood flow and volume, metabolism and metabolic rate, and then into thermoregulatory control systems. From a biophysical and heat transfer perspective, the four main avenues of heat exchange from the heat balance equation (Eq. 1) must be integrated both within the human body ('skin-in'), between the human and clothing (the microenvironment or 'skin-out'), and within the outside environment itself. These pathways of heat exchange include conduction (K), convection (C), radiation (R), and evaporation (E); where conductive transfer is from direct contact with solid objects (e.g., hot or cold surfaces); convective transfer is from fluid or vapor contact (e.g., air or water); radiative exchange is by electromagnetic waves (e.g., solar or infrared); and evaporative heat loss is from liquid to vapor (e.g., sweat, respiratory water loss). From a simplistic perspective, mathematically describing the heat exchange or human heat influence can be described based on the heat balance equation (Eq. 1). This equation shows predicted heat rise or fall from the balance of heat storage (S), calculated by the sum of heat produced, heat gained, and the heat dissipated through the four main pathways of heat exchange:

$$S = (M + W) \pm R \pm C \pm K - E \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] (\mathbf{Eq.\,1})$$

where M represents metabolic heat required based on living and W is metabolic heat produced from active work rate.

For these modeling methods to work, a basic understanding of environmental conditions is required (i.e., what the conditions are) at a minimum. However, for these methods to optimally work, a deeper understanding is required based on the interacting effects of different measures (e.g., wind or air movement impact on temperature).

What variables are required?

In order to capture the minimum inputs for modeling, there need to be considerations for quantifying four main categories, 1) the human (anatomy, physiology, health status, etc.), 2) their activity (metabolic rate from work), 3) the environmental conditions, and 4) their clothing properties. In addition, there is an inherent requirement for an input for duration or time. These categories are described in more detail below; while Table 1. provides some general inputs required or often used within these models. Simplification of inputs can be done mathematically, but it should be assumed with less detailed inputs there will likely be less accurate outputs.

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Table 1. Required inputs for modeling human thermophysiological responses.

	HUMAN	ACTIVITY	ENVIRONMENT	CLOTHING
VARIABLES	Body mass	Metabolic Rate	Air or water Temperature	Insulation
	Initial core body temperature	Total work (watts)	Relative Humidity	Thermal resistance
	Body surface area	External work (watts)	Radiant Temperature	Evaporative resistance
	Height	Static / dynamic	Wind velocity	Wind effects
	Body fat (%)		Air quality	Wet / Dry
	Age		Ambient vapor pressure	Mass
	Sex		Wet bulb temperature	Thickness
	Hydration status		Dew point temperature	Surface area coverage
	Acclimatization (days)		Natural Wet bulb temperature	Layers
	Comorbidities		Altitude	Spectrophotometry
	Initial skin temperature		Carbon dioxide level	Absorption rate
	Resting heart rate		Outdoor / indoor	Dry rate
	Fitness (e.g., VO_{2max})		Terrain	
			Rain, Snow, etc.	

Note: Highlighted variables are 'minimum required'

1. The human: The minimum inputs for the human are related to the human size (body mass, body surface area (BSA)), as these can be used simplistically as a measure for the calculation of resting or basal metabolic rate. Historically a person's size (represented by BSA; m^2) can be used to calculate a resting metabolic rate (RMR) based on an assumed heat production of 58.2 W/m^2 (or BSA * 58.2 = RMR). For example, an average individual of 1.8 m2 will have a resting (minimum value of M) of 1.8 * 58.2 = ~105 W. This single value for the individual (BSA) can also be extended to units of METS (or metabolic equivalents), where 1 MET is resting for that given individual, and progressively the increase numerically is assigned with greater work intensity. From this stance, there are large compendiums published (47) that attempt to apply MET values to specific tasks (which can then be back calculated based on BSA to determine a total metabolic rate in watts).

The next main set of elements relate to the individual's initial thermal status or an initial core body (Tc) or skin (Tsk) temperatures, etc., as this provides the initial calculation point for the model. If this value is not known, a normal value of ~37.0 °C can be used, or assumptions can be made with caution depending on intended use (e.g., conservativeness). Additional information can be used to refine the individual (sex, age, body composition) and to outline potential influencing factors for that individual (fitness, comorbidities); while some values are generally important as they are known to directly influence heat gain/storage (e.g., hydration status, acclimatization). Additionally, is the consideration for complex changes such as rewarming after cold exposure (48, 49). Common methods for estimating BSA are shown in Table 2; while methods for calculating or predicting skin blood flow are show in Table 3.

Table 2. Common methods for calculating or estimating body surface area for thermal models.

Prediction	Formula	Short Reference (#)
Body Surface Area (m^2)	$0.0003207 \cdot Ht^{0.3} \cdot (1000 \cdot Wt)^{0.7285-0.0188 . \log_{10}(1000 \cdot Wt)}$	Boyd, 1935 (50)
	$0.007184 \cdot Ht^{0.725} \cdot Wt^{0.425}$	Du Bois and Du Bois, 1916 (51)
	$0.008883 \cdot Ht^{0.663} \cdot Wt^{0.444}$	Fujimoto et al., 1968 (52)
	$0.0235 \cdot Ht^{0.42246} \cdot Wt^{0.51456}$	Gehan and George, 1970 (53)
	$0.024265 \cdot Ht^{0.3964} \cdot Wt^{0.5378}$	Haycock et al., 1978 (54)
	Female: $0.0051 \cdot Ht^{0.8516} \cdot Wt^{0.3262} \cdot e^{0.0036 \cdot BMI}$ Male: $0.0051 \cdot Ht^{0.8516} \cdot Wt^{0.3262} \cdot e^{0.0036 \cdot BMI} \cdot e^{-0.0120}$	Kuehnapfel et al. 2017 (55)
	$0.1173 \cdot Wt^{0.6466}$	Livingston and Lee, 2001 (56)
	Female: $0.013546 \cdot Ht^{0.5832} \cdot Wt^{0.4470}$ Male: $0.010977 \cdot Ht^{0.6335} \cdot Wt^{0.4348}$	Looney et al., 2020 (57)
	Female: $0.013546 \cdot Ht^{0.3291} \cdot Wt^{0.4414} \cdot As^{0.2578}$ Male: $0.010245 \cdot Ht^{0.3548} \cdot Wt^{0.4284} \cdot As^{0.2956}$	Looney et al., 2020 (57)
	Female: 0.010280·H0.6496·M0.4274 Male: 0.011971·H0.6327·M0.4098	Looney et al., 2023 (58)
	$(Ht + Wt - 60)/100$	Mattar, 1989 (59)
	$0.1053 \cdot Wt^{2/3}$	Meeh, 1879 (60)
	$\sqrt{Ht \cdot Wt/3600}$	Mosteller 1987 (61)
	Female: $0.000975482 \cdot Ht^{1.08} \cdot Wt^{0.46}$ Male: $0.000579479 \cdot Ht^{1.24} \cdot Wt^{0.38}$	Schlich et al., 2010 (62)
	$0.0097 \cdot (Ht + Wt) - 0.545$	Sendroy and Cecchini, 1954 (63)
	$0.00949 \cdot Ht^{0.655} \cdot Wt^{0.441}$	Shuter and Aslani, 2000 (64)
	Female: $0.01474 \cdot Ht^{0.55} \cdot Wt^{0.47}$ Male: $0.01281 \cdot Ht^{0.6} \cdot Wt^{0.44}$	Tikuisis et al., 2001 (65)
	$0.00713989 \cdot Ht^{0.7437} \cdot Wt^{0.404}$	Yu et al., 2010 (66)

Notes: BMI, body mass index (kg/m^2); e, Euler's number; Ht, height (cm); Wt, weight (kg); As, armspan (cm).

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Table 3. Common methods for predicting skin blood flow in thermoregulatory models.

Prediction	Equation	Units	Reference(s)
Cutaneous blood flow (q_s)	$q_s = q_{s,r} \cdot AVD \cdot CVCM \cdot CVCL \cdot CVCE$	mL·100mL tissue^{-1}·min^{-1}	(23, 67-71)
Skin vasodilation (dilat)	$dilat = \beta_{dil,1} \cdot error_1 + \beta_{dil,2} \cdot (warms - colds) + \beta_{dil,3} \cdot warm_1 \cdot warms$	L·h^{-1}	(72)
Skin vasoconstriction (stric)	$stric = \beta_{str,1} \cdot error_1 + \beta_{str,2} \cdot (warms - colds) + \beta_{str,3} \cdot cold_1 \cdot colds$	L·h^{-1}	(72)
skin blood flow (bf_s)	$bf_s = 0.53 \cdot bf_{forearm} - 0.83$	mL·min^{-1}	(73)
local blood flow (lq_s)	$lq_s = \frac{q_{s,r} + \gamma_{dil} \cdot dilat}{1 + \gamma_{str} \cdot stric} \cdot Q_{10}^{\frac{T-T_0}{10}}$	L·h^{-1}	(72)
Muscle blood flow (q_m)	$q_m = q_{m,r} + c_m \cdot \Delta M_w$	L·h^{-1}	(72)
Muscle blood flow (bf_m)	$bf_m = 0.47 \cdot bf_{forearm} + 0.83$	mL·min^{-1}	(73)

Note: q_s and $q_{s,r}$ are skin blood flow and rate; *AVD* is active vasodilation; *CVC* is cutaneous vascular conductance- addition of *M* (mediated), *L* (locally), and *E* (effect of exercise); β_{dil} and β_{str} are control coefficients for vasodilation and vasoconstriction; *warms* and *colds* refer to calculated net warm and cold receptors; $bf_{forearm}$ is blood flow at the forearm; γ_{dil} and γ_{str} are distribution coefficients for vasodilation and vasoconstriction; c_m is a proportionality coefficient; and M_W is metabolic heat produced from exercise

Table 4. Common methods for predicting shivering related model calculations.

Prediction	Equation	Units	References
Total Shivering ($TOTM_{shiv}$)	$= 300 \cdot (T_h - T_{h,set}) + 1.35 \cdot (\sum_{m=1}^{14} W_{a,m} \cdot (\dot{q_{s,m}} - q_{s,set,m}) + 75 \cdot (\sum_{m=1}^{14} W_{a,m} \cdot (T_{s,m} - T_{s,set,m})$	Kcal·h^{-1}	(74)
Maximal Shivering ($Shiv_{max}$)	$= 30.5 + 0.348 \cdot VO_{2max} - 0.909 \cdot BMI - 0.233 \cdot age(yrs)$	mLO_2·kg^{-1}·min^{-1}	(74)
Metabolic Rate of Shivering (M_{shiv})	$= 60 \cdot (36.6 - T_{ty}) \cdot (34.1 - T_s)$	Kcal·h^{-1}	(5)
Metabolic Rate of Shivering (M_{shiv})	$= 36 \cdot (36.5 - T_{ty}) \cdot (32.2 - T_s) + 7 \cdot (32.2 - T_s)$	Kcal·h^{-1}	(75)
Metabolic Rate to open air (M1)	$= 41.31 - 57.77 \cdot \frac{dT_s}{dt} - 5.01 \cdot (T_s - 34)$	W·m^{-2}	(76)
Total Metabolic Rate (M2)	$= M1 + (894.15 - 23.79 \cdot T_{re})$	W·m^{-2}	(76)
Total Metabolic Rate (M)	$= 0.0314 \cdot (T_s - 42.4) \cdot (T_{re} - 41.4)$	W·kg^{-1}	(77)
Metabolic Rate of Shivering (M_{shiv})	$= \frac{155.5 \cdot (37 - T_{es}) + 47 \cdot (33 - T_s) - 1.57 \cdot (33 - T_s)^2}{\sqrt{BF\%}}$	W·m^{-2}	(78)

Note: *T* is temperature; $_h$ is head; set is set point of temperatures; $W_{a,m}$ is a weighting coefficient; q_s is heat flux $_s$ is skin; *BMI* is body mass index; $_{ty}$ is Tympanic membrane; $_{re}$ is rectal; and $_{es}$ is esophageal; *BF%* is body fat percentage

Table 5. Suggested methods for predicting metabolic rates during walking, running, or standing.

Prediction	Equation	Units	References
Metabolic rate based on speed	$= 1.44+1.94 \cdot S^{0.43}+0.24 \cdot S^4$	$W \cdot kg^{-1}$	(79)
Metabolic costs with backpacks, varied terrain, or with weighted vests	$=\dot{M}_{Rest} + (\dot{M}_{stand} + 1.78 \cdot S^{0.58} + 0.27 \cdot S^4) \cdot (1 + 1.96 \cdot {L_B}^{1.36} + 1.38 \cdot {L_{Vs}}^{1.21}$	$W \cdot kg^{-1}$	(80-83)
Metabolic cost of running on level terrain	$= 4.43 + 1.51 \cdot S + 0.37 \cdot S^2$	$W \cdot kg^{-1}$	(84)
Terrain coefficients for land human locomotion	$\eta_{treadmill}=1.0$, $\eta_{paved\_road}=1.0$, $\eta_{dirt\_road}=1.2$, $\eta_{gravel\_road}=1.2$, $\eta_{swamp}=3.5$, $\eta_{slippery}=1.7$, $\eta_{sand}=1.5+\frac{1.3}{V^2}$, $\eta_{vegitatoin}=0.0718V^3 + 1.3V^2 - 5.3701V + 6.0705$	η	(85)
Terrain coefficients for land human locomotion over snow	$\eta_{snowshoes} = 2.7$ $\eta_{over\_snow} = 0.0005z^3 + 0.0001z^2 + 0.1072z + 1.2604$	η	(86)

Note: G is grade (° for ref 125, % for others); Ht, height (inches for ref 129); L, external load (kg); M, mass (kg); η, terrain factor; S, speed (mph for ref 129, $m \cdot s^{-1}$ for others); $VO_{2\text{-rest}}$, resting oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$); Wt, weight (lbs), ***η***, terrain coefficient, and z, snow depth.

2. Activity (metabolic rate): Metabolic heat produced by an individual generally imposes the largest impact on the amount of heat gained or stored by the person. For example, if a person is generating a high amount of metabolic heat from work (e.g., running a marathon) he or she is still at an increased risk of a heat injury when the environment is very cold. Typically, this metabolic rate is calculated or estimated, but expressed in units of watts, as this is more related the balance of heat (e.g., units of kcals would need to be converted to a heat related value). Similar to the calculation of RMR, an interpretation of an individual's metabolic rate can be simplified based on the individual's BSA and an active increase. This can utilize a set of calculations using a given MET rate or based on inputs related to a total metabolic demand (34, 87).

Additionally, within the context of metabolic heat production, there is often a modeled distinction between energy that goes directly (more efficiently) toward work and less for heat production. A simplified method has been used during walking activities to use an 80/20 ratio of RMR and work rate (W) and external work (Wex). This assumption is based on a best-case efficiency of energy to heat. However, it is understood that these efficiencies will change based on conditions (e.g., certain activities are more or less efficient at using energy for meaningful work) (88). Common methods for calculating metabolic rate for shivering are shown in Table 4; while methods for predicting total metabolic rates are shown in Table 5.

3. The environment: Generally, there are minimum essential environmental inputs required in order to account for the human impact based on the exposed conditions, including air temperature (Ta), relative humidity (RH), and wind velocity (Vw). However, as conditions become more specific, more inputs are required to ensure biophysical interactions are correctly captured. For example, in fully immersed conditions water temperature (Tw) is required; while in partially immersed conditions the addition of water turbulence could be of value (e.g., heat transfer in still water ≠ turbulent water). Additionally, as there are complex interactive effects between human physiology, physics, and the environment, the more details provided as inputs likely influence the accuracy of the modeled outputs (Table 1 provides a list of variables given certain scenarios).

Table 6. Common equations used for evaluation of clothing biophysical properties.

Variable (unit)	Equation	Comment	Reference
Thermal Resistance *(R_t* (m^2K/W))	$R_t = \frac{(T_s - T_a)}{Q/A}$	Thermal resistance (R_t) is the dry heat transfer from the surface of the manikin through the clothing and into the environment. Measured at 0.4 m/s	(89)
Evaporative resistance *(R_{et}* (m^2Pa/W))	$R_{et} = \frac{(P_{sat} - P_a)}{Q/A}$	Evaporative resistance (R_{et}) is heat loss from the body in isothermal conditions ($T_s \approx T_a$). Measured at 0.4 m/s	(90)
Clo (N.D.)	6.45(IT)	I_T is the total insulation including boundary air layers. Measures of R_t can then be converted to units of clo, where 1 clo = 0.155 m^2K/W.	(91-94)
Vapor permeability index *(i_m (N.D.))*	$i_m = \frac{60.6515 \frac{Pa}{°C} R_{ct}}{R_{et}}$	Measures of R_{et} can then be converted to a vapor permeability index (i_m), a non-dimensional measure of water vapor resistance of materials.	(91-94)
Evaporative potential *(i_m/clo (N.D.))*	i_m/clo	Calculated from Rt and Ret, typically reported at a wind velocity of 0.4 m/s.	(91-94)
Intrinsic insulation *(I_{cl} (N.D.))*	$I_{cl} = I_t - \left(\frac{I_a}{f_{cl}}\right)$	I_a is insulation measured on a nude thermal manikin, I_t is total insulation	(95-97)
Clothing area factor *(f_{cl} (N.D.))*	$f_{cl} = \frac{A}{A_{cl}}$	Element used to describe wind-related effects on clothing properties.	(95-97)
Empirical cold clothing area factor *(f_{cl} (for cold))*	$f_{cl} = 1.0 + .3 \cdot I_{cl}$	Simplified or estimated A_{cl} and f_{cl} is often used where a value of 1 is assumed for warm-weather or indoor clothing. For cold-weather clothing a value would be calculated here empirically.	(95)
Estimated clo at 1m/s wind velocity (*clo@ 1m/s (N.D.)*)	clo@1m/s = $clo(0.782) - im(0.827) + 0.333$	Empirically derived methods of estimating clo value at 1 m/s from standard measure of 0.4 m/s.	(94, 98)
Wind effect gamma value *(cloVg (N.D.))*	cloVg@1m/s = $clo(0.079) - im(0.516) - 0.182$	Empirically derived methods of estimating clo wind effect (g) value from standard measure of 0.4 m/s.	(94, 98)
Estimated i_m/clo at 1m/s wind velocity *(i_m/clo@ 1m/s (N.D.))*	i_m/clo@1m/s = $i_m/clo(1.48) - 0.04$	Empirically derived methods of estimating i_m/clo value at 1 m/s from standard measure of 0.4 m/s.	(94, 98)
Wind effect gamma value *(i_m/cloVg (N.D.))*	i_m/cloVg@1m/s = $i_m(0.466) - clo(0.068) + 0.216$	Empirically derived methods of estimating i_m/clo wind effect (g) value from standard measure of 0.4 m/s.	(94, 98)

Notes: Ts is surface temperature and Ta is the air temperature, both in °C or °K. Q is power input (W) to maintain the surface (skin) temperature (Ts) of the manikin at a given set point; A is the surface area of the measurement in m2. IT is the total insulation including boundary air layers. Evaporative resistance (Ret) is heat loss from the body in isothermal conditions (Ts ≈ Ta) Psat is vapor pressure in Pascal at the surface of the manikin (assumed to be fully saturated), and Pa is vapor pressure, in Pascal, of the chamber environment. I_a is insulation measured on a nude thermal manikin, I_t is total insulation, A (m^2) is surface area of the nude manikin, and A_{cl} (m^2) is surface area the clothed manikin.

4. Clothing: Inputs related to clothing typically required biophysical properties to describe heat transfer (dry or evaporative) through them and into the environment or as an interpretation of how much heat is retained within them (e.g., insulation). These values are typically calculated from standardized biophysical tests for thermal and evaporative resistances (Rt, m^2°C/W and Ret, m^2Pa/W) (ASTM F1291-16 & ASTM F2370-16 (89, 90)). While these simple inputs provide insights to the clothing properties on their own, it is often required to have additional elements considered such as the influence of air flow on them (94, 98-100) or the influence of solar on the materials themselves (101). Along with each of these, it is important to understand the mass of the clothing, as it directly influences an energy cost to the wearer, as well as the surface coverage of the clothing (or amount of uncovered area from clothing), and the number of layers of clothing (99, 100, 102, 103). Conceivably, other values can be incorporated within these models that would account for unique conditions, such as absorption and drying rates and the associated biophysical aspects of partial or fully wetted clothing (37, 104-107). A summary of some commonly used equations for describing biophysics of clothing are shown in Table 6.

Chronology of Important Publications / Developments

Table 7 chronologically lists a collection of human thermal models, key concepts, and equations that have shaped the field. While this list does not contain every addition to the field; it describes intended uses, added comments, and provides their main references.

Table 7. Chronological list of important publications related to the advancement of thermoregulatory modeling.

Year	*Comments*	*Reference Original/Key*	*Reproducible (Source code)*
1770	Sir Charles Blagen described differences in thermoregulation; 'man, dog, and beefsteak model' in a hot environment	(108)	N/A
1822	Fourier described mathematical law for heat balance between solids	(109)	Yes
1911	Lefevre conceptually described heat exchange between the human and environment. Human as a sphere with an internal core and external shell.	(110)	N/A
1934	Burton applied Fourier's law, presenting concept of the human as a cylinder with thermoregulation.	(111)	Yes
1941	Gagge, Burton and Bazett outline a method of standardization of units and terms in thermoregulation modeling	(112)	N/A
1946	Adolph and Molnar described heat exchange and tolerance for man in cold environment.	(113)	N/A
1946	Molnar described hypothermia and survival of man in the ocean environment.	(114)	N/A
1947	Nelson et al from the Armored Medical Research Laboratory describe wartime estimations of convection and evaporation	(115)	N/A
1948	Pennes described tissue temperatures and blood, allowing for the creation of a bioheat equation.	(116)	Yes
1957	Molnar describes one of the first attempts of calculating heat balance for hand temperatures in the cold.	(117)	N/A

1961	Crosbie describes the first concept of a multi-node thermal model.	(118)	Yes
1961	Wissler published his first iteration of a multi-element thermoregulatory model.	(119)	Yes (on hand)
1964	Wissler improved upon and further described his multi-element model.	(22)	Yes (on hand)
1966	Stolwijk & Hardy developed a model of thermoregulation.	(5)	Yes
1971	Wissler described and compared simple 14-node modeling to expanded 250-node model.	(120)	Yes (on hand)
1971	Stolwijk & Hardy described their model human with spherical head and five cylindrical segments	(6)	Yes
1971	Gagge developed a simplified model for personnel working in an indoor environment.	(121)	Yes
1971	Givoni-Goldman developed an early metabolic cost prediction method specifically targeted for thermal modeling.	(25)	Yes
1972	Givoni-Goldman first method for empirically predicting core body temperature based on clothing, environment, and activity.	(26)	Yes
1974	Montgomery adapted a model applicable to Stolwijk design, for immersion in cold water.	(16)	Yes (on hand) (122)
1974	Montgomery applied his model specifically to scuba divers and their environment.	(17)	Yes (on hand) (122)
1974-1976	Gordon developed and expanded modeling to include characterization of transient cold exposures.	(74, 123)	Yes (122)
1975-1976	Kuznetz developed the 41 Node NASA model.	(124, 125)	Yes
1976	Montgomery improved model resolution to focus changes to forearm, hands, fingers.	(126)	Yes
1979	Kuznetz refined a two-dimensional transient model.	(127)	Yes
1980	Stolwijk reviewed and refined modeling approaches.	(128)	Yes
1988	Tikuisis described basis and approach for modeling in cold water immersion, to include varied body composition. This formed the basis of the cold thermoregulatory model (CTM).	(129-131)	Yes (on hand)
1989	Lotens developed and described a 2-node model specifically for temperature of the foot.	(132)	Yes
1989	Werner and Buze described a comprehensive three-dimensional dynamic thermoregulatory model.	(7)	Yes
1991	Smith doctoral thesis described an early concept of a usable three-dimension thermoregulatory model.	(133)	Yes
1991-1992	Ducharme and Tikuisis described a finite element (FE) approach to modeling forearm muscle temperatures.	(134, 135)	Yes
1991-1998	Shitzer developed and refined modeling specific to hands and fingers using numerical and cylinder-based approaches.	(136-147)	Yes (on hand) (148)
1991-1997	Kraning developed a single-cylinder, multi-node rational model (SCENARIO). Later refined and described in full detail.	(28, 30)	Yes (on hand)
1992	Lotens described a whole-hand thermal model.	(149)	Yes
1993-1997	Werner and Webb outlined the first basis of the six-cylinder model (ThermoSim). Later this was adapted and improved by	(8, 9)	Yes (on hand) (148)

	Xu and Werner, as the six-cylinder thermoregulatory model (SCTM)		
1995-1997	Tikuisis quantified human survival in the cold and in immersed conditions.	(150, 151)	Yes
1995	Fu outlined a three-dimensional model to include aspects related to clothing.	(152)	Yes
1999	Fiala developed comprehensive thermoregulatory model that accounts for both comfort and heat stress. Notably, this is the most cited thermal model.	(44, 45)	Yes
2001	Malchaire et al., published the predicted heat strain (PHS) model.	(153)	Yes
2001	Havenith outlined the rational basis of an individualized thermoregulatory model for heat stress.	(154)	Yes
2002	Tanabe model designed as a multi-node comfort focused model.	(155)	Yes
2002-2007	Tikuisis quantified modeling of facial cooling.	(156, 157)	Yes
2002	Khori and Mochida distributed a version for a two-node thermal model, advanced from Gagge.	(158)	Yes
2003-2022	SCENARIO model was refined and mathematically described for open use.	(39, 40, 159)	Yes
2004	Tikuisis quantified thermal responses specific to finger temperatures.	(160)	Yes (on hand) (148)
2005	Xu quantified thermal responses specific to foot temperatures and footwear.	(161)	Yes
2008	Wissler quantified skin blood flow in a usable format for thermoregulation modeling.	(23)	Yes (on hand)
2008-2014	Xu et al., developed the Probability of Survival Decision Aid (PSDA) as a software variant of the SCTM model. PSDA transitioned to the U.S. Coast Guard for mandated use in search and rescue operations.	(11, 12)	Yes (on hand)
2009	Munir updated and reviewed the Stolwijk 25-node model.	(162)	Yes
2009	Takada developed and described an individualized thermoregulatory model.	(163)	Yes
2009	Ferreira and Yanighara developed and described a transient three-dimensional thermoregulatory model.	(164)	Yes
2011	Foda and Siren provided updates to the Gagge model.	(165)	Yes
2004	Kingma adapted a model (ThermoSEM) based on an initial baseline from the Fiala model.	(166)	Yes
2012	Kingma provided updates for a modeling approach that incorporates neurophysiological elements.	(167)	Yes
2013	Kobayashi and Tanabe released an adapted version from Stolwijk that included improved vascular components; the JOS-2 model.	(168)	Yes
2012-2013	Berglund et al., refined a rational modeling approach to enable predicting of thermophysiological responses to an enclosed submarine space.	(107)	Yes
2013-2016	UK Defence and U.S. Army worked to modify the Wissler model into a working variant for divers, specifically tailoring	N/A	Yes (on hand)

	for adjusting of clothing/suits. The Wissler Apparel Requirements Model (WARM).		
2016	Lai and Chen expand on the Fiala model with longitudinal and radial thermal gradients.	(169)	Yes
2017-2021	Potter and Friedl made incremental updates and improvements to the hybrid model, the heat strain decision aid (HSDA).	(34-38, 170, 171)	Yes (on hand)
2019	Ioannou et al., published an open source software variant of the Predicted Heat Strain (PHS) model.	(172)	Yes
2019-2021	Xu et al., developed the Cold Weather Ensemble Decision Aid (CoWEDA) as a variant of SCTM used specifically for planning cold weather operations.	(14, 15, 173)	Yes (on hand)
2022	Yermakova outlined multi-node model for heat stress environmental conditions, the Heath Risk Prediction (HRP) model.	(20, 21, 174, 175)	Yes
2021	Takahashi developed and provided code for a model adapted from Stolwijk's design, and expanded on the JOS-2, developing the JOS-3 model.	(176)	Yes
2021-2024	Castellani & Xu provide mathematical advancements to development of a finite element thermoregulatory model for men and women.	(3, 4, 41)	Yes
2022	Potter and Friedl describe the use of thermoregulatory models for military tactical advantages.	(177-179)	Yes
2024	Yermakova modeled differences between varied state head and body immersion and tailored a comprehensive model (HRP) into a mobile application.	(2, 180)	Yes

DISCUSSION

Mathematical modeling of thermal physiology has come a long way since the elegant qualitative experiments of Sir Charles Blagden in 1770, comparing responses to heat exposure for a man, a dog, and a beefsteak in a hot room (108). Since then, the quantitative relationships have been described and modeled through several different approaches including empirical and mechanistic, and then assembled in whole body, segmented cylinder, or complex systems-based approaches.

The Wissler model in the 1960s provided an early basis for most subsequent models. Originally, this model divided the body in 15 geometric regions (head, thorax, abdomen, and then arm and leg segments) and estimated heat transfer from large arteries and veins to other tissues and estimating properties such as thermal conductivity and blood flow rates to small vessels (22). The constantly evolving Wissler model(s) was adopted into early military applications such Air Force recommendations for clothing protection during cold water immersion (181, 182).

A different approach to cold water immersion predictions was developed by NASA. The Montgomery model was based on a physical-controlled system (i.e., body segments and their thermal exchange paths) and a dynamic-controlled system (i.e., afferent and efferent signals managed through a hypothalamic integrator maintaining thermal homeostasis). The model components (WETMAN and SIZE) were extensively tested and refined with human cold water immersion studies (16). The Montgomery model was used to predict core temperature of divers in a range of water temperatures, protective clothing, duration of dives, and with different breathing gas mixtures (17).

Tikuisis developed the three-cylinder cold thermoregulatory model (3-CTM) which included personalized variables such as body composition (129, 131) and metabolic heat production from shivering. The model consisted of one cylinder representing the body and a layer for fat and an additional layer for clothing. This model was used to predict cold water survival time based on predicted core temperature (<30°C) (150, 151). Werner and Webb developed a six-cylinder model (6-CTM: "Thermosim") (8), a substantial improvement over earlier 3-CTM efforts. This was further developed by Xu and Werner and incorporated basic principles from the Montgomery model and body properties from Stolwijk and Hardy to provide better predictions of temperatures in the hands and feet. Xu and Werner divided each segment in core, muscle, fat, and skin layers; and considered vasomotor changes, metabolic heat, and sweat (9). The current U.S. Army Probability of Survival Decision

Assist (PSDA) model was developed by Xu on the basis of the 6-CTM (SCTM) and has been implemented for search and rescue applications by the U.S. Coast Guard (9, 11, 12). This has been further enhanced to develop the Cold Weather Ensemble Decision Aid (CoWEDA) application for prediction of clothing, activity, and ambient cold conditions to predict core temperature (hypothermia risk) and peripheral (hand and feet) temperatures and freezing cold injury risk (14, 15, 173).

Important and highly cited efforts from Fiala et al. (44, 45) contributed organized and comprehensive thermoregulatory models that have been used primarily to predict individual thermal comfort for personal comfort systems or indoor building environments. Notably, the 'Fiala model' has advanced the field of thermophysiology by expanding accessible method into several fields of study and consumer uses, to include the automotive industry, clothing evaluations, clinical aspects, built environments, and others. Continuous evolution of these human comfort models such as the joint system thermoregulation model (JOS-3) have increased complexity (e.g., 83 nodes) (176) with key outputs related to comfort such as predicted skin temperatures. Kingma has developed a model ("ThermoSEM") (166, 167) derived from Fiala model principals.

CONCLUSIONS

This brief review highlights some of the origins and end-states of the more widely used modeling methods. These methods have been applied to a variety of exposure types (e.g., space, cold, heat, immersion) and for various use cases (survival times, risk mitigation, tactical planning, etc.). There is a clear abundance of scientific direction and investment placed on developing these base modeling methods as well as a clear need for continued advancement of them for unique scenarios (i.e., transition between conditions) as well as for individualization. A key continued next step for each of these methods is to improve accuracy of individual predictions and to translate models / methods into broader use, to allow for model validation and improvements.

It is apparent that immersion cold modeling has been driven almost exclusively by military needs. There is no predictive model that is fully adequate for the prediction of core temperature, extremity temperatures and function, and metabolic limits (mental and physical endurance limits) for diving and cold water swimming.

Conflicts of interest. The authors certify that there are no conflicts of interest to report.

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