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MATHEMATICAL MODEL OF HUMAN RESPONSES TO OPEN AIR AND WATER IMMERSION

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ABSTRACT
Mathematical models that describe human thermoregulatory responses provide valuable information that can be used to prevent thermal injuries (e.g., heat or cold related), for training or planning purposes, and for an array of simulation activities such as analyzing after actions assessments. This paper focuses on the structure and mathematical basis of a multi-compartment model specifically designed and validated for use in a wide range of conditions, to include hot and cold stress and immersion in both cold and warm water conditions, that includes methods for assessing responses with various clothing. The Health Risk Prediction model (HRP) uses inputs environmental conditions, clothing properties, individual characteristics, and activity rates to quantitatively generate predictions of body temperatures (skin, muscle, core temperatures, etc.) as well as physiological outcomes (skin blood flow, metabolism, cardiac output, shivering, etc.).

Keywords: physiology, biophysics, thermoregulation, clothing, environment, modeling

INTRODUCTION

For as long as humans have interacted with the environment, there has been an interest in understanding and quantifying the responses to various conditions. As the conditions and physiological responses differ between conditions, often modeling approaches were taken specific to an environment. Each environmental thermal stressor condition (hot, cold, immersion, space, etc.) poses unique challenges that change both the physical conditions as well as the physics basis for modeling the thermal interaction of the human and environment.

Some of the earliest documented studies assessed heat stress; where Charles Blagden conducted simple experiments comparing the responses of man, dog, and beef steak while exposed in a hot room (1). While the quantification of this exchange between the human and the environment was later described by Lefevre in 1911; where the human was described as a sphere with an internal core that exchanged heat through the shell/skin into the environment (2).

In 1934, Burton mathematically described this relationship, applying Fourier's 1882 Law of heat balance in solids (3), specifically for heat exchange in humans, representing the human as a single cylinder (4).

During heat exposure, a humans' thermoregulation systems allows them the ability to compete with the environment, by dissipating heat mainly through evaporation (e.g., sweat, respiratory). While they are also able to exchange heat via the other convensional pathways (conduction, convection, and radiation). During heat exposure, the main injuries of concern are typically due to whole-body heat gain (e.g., hyperthermia, heat stroke, heat exhaustion) (5-7).

In contrast to heat stress, modeling cold conditions the focus is more often total (whole-body) heat loss (e.g., hypothermia) or regional (hands, feet, etc.) injuries (e.g., frostbite) (8, 9). One of the more notable attempts to first quantify this relationship came from Molnar, specifically studying heat balance in the hand during cold exposure (10). Following this work, several other important improvements have been made specific to hands, fingers (11-18), feet and toes (19, 20), and facial soft tissue (21, 22).

Interestingly, much of the pioneering research that has helped push the art of mathematical modeling of human physiology has come from the push to into outerspace. Most notably is the work of Professor Jan Stolwijk, who developed one of the earliest versions of a comprehensive physiological modeled built on rational principles, to include temperature setpoints and a negative feedback design into a 25-node model (23-25). The work from Stolwijk was later expanded by Kuznetz, who expanded the model to a 41-node system specifically tailored for modeling needs of the National Aeronautics and Space Agency (NASA) (26).

In contrast to both open air heat or cold stress, water immersion poses an extreme and unique challenge, limiting avenues of heat exchange to almost entirely conduction. One of the most notable improvements for modeling human immersion came from an adaption of Stolwijk's model by Montgomery, who adapted coeficients, additional layers for individual nodes, and a computational framework for human scaling specific to divers (27, 28). Critical improvements to the initial work of Stolwijk and adaptations from others, have been made by Tikuisis et al., who refined modeling responses to cold water immersion that better accounted for shivering and refinement of heat exchange within the human system (29, 30). Later studies have specifically refined immersion responses to include immersion level (31, 32), body composition differences (33), and survival time (34-38).

While much of the focus of immersion modeling has been in cold water; there are significant impacts of warm water exposure (39-43) that are becoming more relevant due to climate change (44, 45). Due to the uniqueness of the natural occurance (to date), a lack of data, and complexity of the conditions, only a few have begun to model these responses (46, 47).

While clothing itself is not an environmental condtion; different clothing systems and environments or activities are often linked by nessecity. Additionally, these clothing systems create a microenvironment that in itself can decrease or increase the thermal stress on humans. Therefore, it is critical that models of human responses include elements that allow for the quantifiable considerations of various clothing properties (48-51).

This paper focuses on the development and structure of a multi-comparement model specifically designed and validated for use in a wide range of conditions, to include hot and cold stress and immersion in both cold and warm water conditions, that includes methods for assessing responses with various clothing.

METHODS

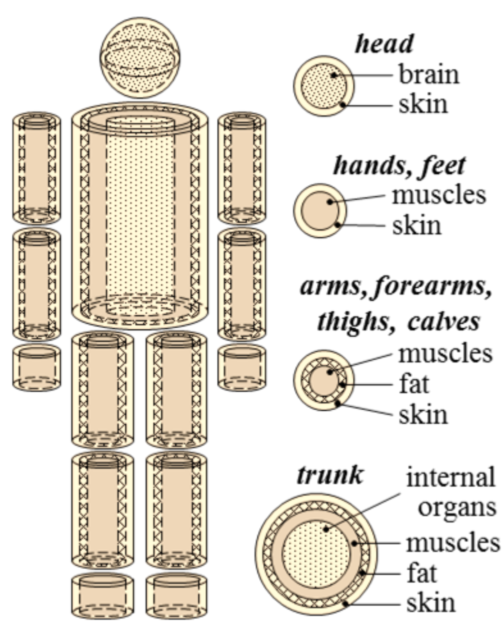
The Health Risk Prediction (HRP) model

The Health Risk Prediction (HRP) model from (52, 53) is a rationally derived method that makes predictions (e.g., core body temperature (*Tc)*, skin temperature (*Ts)*, and sweat rate) are calculated based on a series of equations built on a rational construct.

The software embodied HRP model typically divides the human into 14 segments (13 cylinders and one sphere) and 39 compartments (38 layers and a blood compartment) (Figure 1). However, specialized algorithms have been developed that allow the modeling method to expand or condense these systems for more or less resolution.

Heat exchange within the model occurs between each of the layers via conductance and by convective heat from blood circulation. The predicted thermal state within each section of the model is calculated based on an energy balance equation from each segment. This balance is calculated based on a collection of both passive and active system equations. Passive systems relay on the basic heat exchange between layers and with the environment (mainly from convection, conduction, and radiation); while active system equations account for thermoregulatory responses (e.g., blood flow rates, sweating, shivering).

Figure 1. Geometric representation of the Health Risk Prediction model (HRP)



The Passive System

Rational functions describe the passive heat transfer between each of the model's compartments (ij). These are seen as:

$$c_{ij}m_{ij}\frac{\Delta T_{ij}}{\Delta t} = M_{ij} + a_{ij-1}\lambda_{ij-1}(T_{ij-1} - T_{ij})$$
$$-a_{ij}\lambda_{ij}(T_{ij} - T_{ij+1}) + c_b\rho_b w_{ij}(T_b - T_{ij})$$
$$-h_{ij}^C A_{ij}(T_{ij} - T_{ie}) - h_{ij}^R A_{ij}(T_{ij} - T_{ie})$$
$$-h_{ij}^E A_{ij}(P_{ij} - P_{ie})$$

where i,j represent compartments and N and K represent the number of cylinders and layers respectively ($i = \overline{1,N}, j = \overline{1,K}$). c = specific heat (kcal/(kg·°C)); m = mass (kg); T = temperature (°C); t = time (h); M = metabolic rate (kcal/h); a = thickness (m); λ = conduction (kcal/(h·m·°C); b = blood; ρ = density (kg/m^3); w = flow; h^C, h^R, and h^E = convective (kcal/(m^2 ·°C·h)), radiative (kcal/(m^2·°C·h)), and evaporative (kcal/(m^2·kPa·h)) heat; A = surface area (m^2); P = vapor pressure (kPa).

This response becomes more complex when there is an interaction or state of full or partial water immersion. In this instance, an additional component would be added to the above equations to include the exchange of heat from the water and consideration of the body surface area impacted ($-Q_{ij}^{Water}$). This addition is mathematically described as:

Added water immersion component:

$$Q_{ij}^{Water} = h_{ij}^{Water}A_{ij}(T_{ij} - T_i^{Water})$$
$$h_{ij}^{Water} = K_{water} \cdot Nu/d_{ij}$$

where K_{water} = thermal conductivity of water; Nu = Nusselt number; d_{ij} = compartment diameter. These elements are also impacted by the effects of movement within the water (54).

Additionally, heat transfer by blood within the body has principal effect on temperatures and heat balance. Heat exchange in large veins is determined by heat flows transported by blood flows from all *ij*-compartments, and includes relationships to cardiac output, and influneces respiratory evaporative heat losses. Where heat transfer equation for blood pooling is represented as:

$$V_b\rho_b c_b\frac{\Delta T_b}{\Delta t} = \sum_{i=1}^{N}\sum_{j=1}^{K} W_{ij}\,\rho_b c_b T_{ij}$$
$$- W_b\rho_b c_b T_b$$
$$- \dot{V}\rho_e r(\rho_{ex} - \rho_{in})$$
$$- \dot{V}\rho_e c_e(T_b - T_e)$$

where V = volume (l); W = blood flow by compartment (l/h); $\dot{V}$ = pulmonary ventilation (l/h); *ex* = expired air; *in* = inspired air; r = evaporative heat (kcal/kg); e = local sweat evaporation (kcal/h).

Active System

Active thermoregulatory responses for maintaining homeostasis in respose to exercise and/or environmental exposure are mathematically described. Specific areas include active skin blood flow, muscle blood flow, sweat rate, heart rate, and metabolic demands of shivering.

Skin blood flow (*Ws*) changes during physical activities and with different environmental exposures (55, 56). Typically, during cold exposure, skin blood flow is decreased to conserve heat within the body; while during heat exposure (or exercise), skin blood flow and sweat evaporation provide the main defense against overheating. Heat is continually transferred to the environment as water is vaporized from surface of the skin. This enables cooling effects on skin as sweat evaporates. Cooled skin in turn serves to cool blood through increase of skin blood flow, this function is mathematically described below as:

Skin blood flow (Ws) (l/h):

$$W_s = W_{s,0} \pm f_1(T_{br,0} - T_{br}) \pm f_2(T_{s,0} - T_s)$$

where W = flow (l/h); s = skin; 0 = initial value; f = sensitivity (kcal/(h·°C); br = brain.

The thermoregulatory response of sweating occurs when brain temperature (T_{br}) increases to a set threshold (T_{th}). Evaporation required is determined by thermoregulatory center sensitivity (*f*) to brain and mean skin temperatures changes, described as:

Sweat evaporation (E) (kcal/h):

$$E = E_0 \pm f_3(T_{br,0} - T_{br}) \pm f_4(T_{s,0} - T_s), \quad if\ T_{br} \geq T_{th}$$

During exercise, the thermoregulatory system is activated by two competing requirements of cardio vascular systems. The first is an increased blood flow to working muscles (W_m) to deliver the oxygen in proportion to exercise intensity, described as:

Muscle blood flow (W_m) (l/h):

$$W_m = W_{m,0} + k_1 \cdot Q$$

where Q = work intensity.

The second demand ensures heat removal of from deep tissues to the periphery that is provided by an increase of skin blood flow (W_s) based on the relationship of work intensity and blood temperature driven by heart rate (H_R), seen as:

Heart rate (H_R) (bpm):

$$H_R = k_2 \cdot Q + k_3 \cdot T_b - d$$

where *d* = constant value.

Shivering response induces an involuntary muscle contraction, off and on, that seeks to incease body temperatures (8, 57, 58). Three variants are used in the model to account for metabolic demands of shivering (M_{sh}), based on interactions and thresholds between values of T_s, T_{br}, Tc, and body fat percentages *(%BF)*, these include:

Metabolic demands of shivering (M_{sh}) (w/m^2):

$$1. Msh = A\left((T_{s,0} - T_s)(T_{br,0} - T_{br}) + 3(T_{s,0} - T_s) + 3(T_{br,0} - T_{br}) + 65\left(\frac{T_{s,0} - T_s}{\%BF}\right)^{1.5}\right)$$

$$2. Msh = A\left(5 * (T_{s,0} - T_s)(T_{br,0} - T_{br}) + 65\left(\frac{T_{s,0} - T_s}{\%BF}\right)^{1.5}\right)$$

$$if\ T_{s,0} - T_s \geq H_s\ and\ T_{br,0} - T_{br} \geq H_{br}$$

$$3. Msh = (155.5\ (37.0 - T_c) + 47.0\ (33.0 - \bar{T}_s) - 1.57\ (33.0 - \bar{T}_s)^2) / \sqrt{\%BF}$$

RESULTS

Two example cases have been used to demonstrate the modeling approach related to a marathon runner in multiple conditions (16, 20, and 24°C; 50% relative humidity, 1 and 4 m/s wind velocity) and an individual in cool water (water temperature 14°C; air temperature 20℃) during a competitive swim race in two different conditions, with and without a wetsuit. Both of these cases use a healthy, normally hydrated male (70 kg; 1.8m^2 body surface area; low body fat 15%).

Inputs and Outputs

As the model can be expanded in its dimentions and computational resolution, it is capable of integrating a large range of input variables. However, from a practical perspective, a user-friendly interface has been developed that simplifies the inputs (Figures 2-3). This interface is designed to require initialization variables related to the human, their metabolic rate, the environmental conditions, clothing properties, specifics related to their immersion status (if applicable), and duration of exposure.

Figure 2. Graphical user interface for the Health Risk Prediction model (HRP) for use in on-land conditions (shown is for an individual in running clothes)

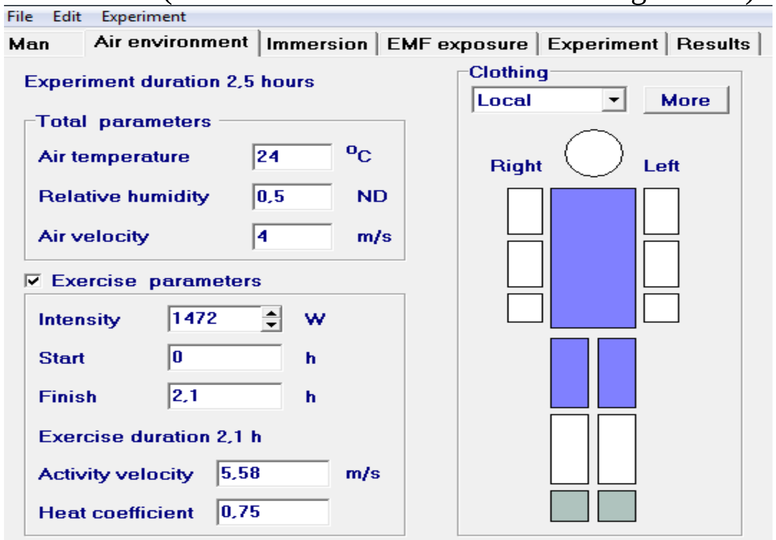
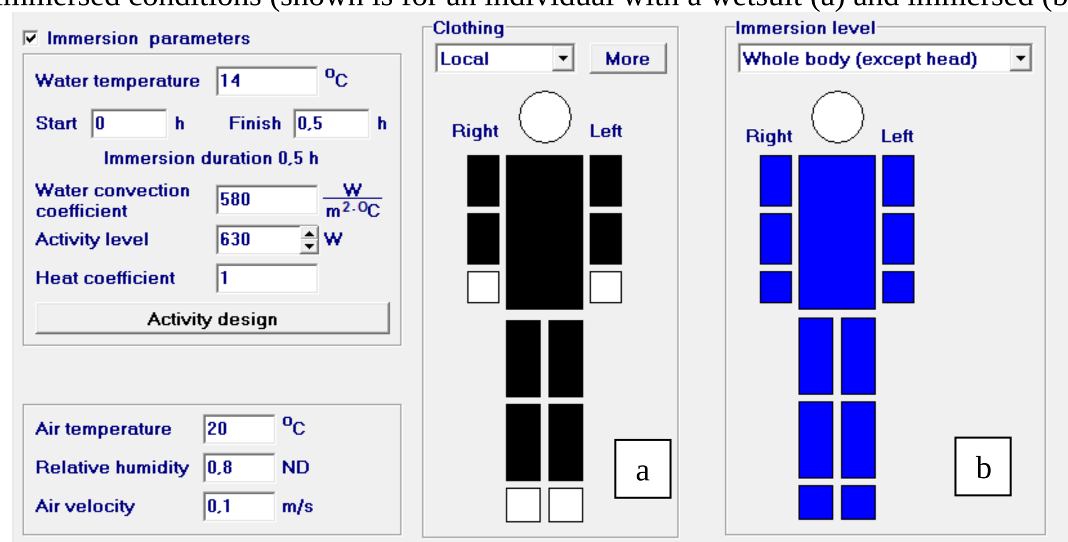


Figure 3. Graphical user interface for the Health Risk Prediction model (HRP) for use in immersed conditions (shown is for an individual with a wetsuit (a) and immersed (b))



Case of the marathon runner

In this example case of a marathon runner starting at a normal initial *Tc* (36.8°C), then running at a high speed (5.58 m/s) over the course of a marathon (42.2 km) with an associated high metabolic demand (1,472W) for approximately 126 minutes. The individual is assumed to be wearing running clothes with minimal surface area coverage and low thermal and evaporative resistance values (0.02 m^2·°C/W and 0.0012 m^2·kPa/W) and running shoes (0.087 m^2·°C/W and 0.052 m^2·kPa/W). Modeling was performed for three environmental temperature conditions (16, 20, and 24°C) in 50% relative humidity and with two different wind velocity conditions (1 and 4 m/s).

Figure 4 shows the compared predicted values of *Tc* over the course of time between the three different environmental conditions. Figures 5-7 show evaporative heat loss (kcal/h), sweat rate (g/h), and total body water loss (kg and % of body weight) for the three environmental conditions. Figure 8 shows modeled differences in a single temperature condition (20°C; 50% relative humidity) with two different wind velocities (1 and 4 m/s); while Figure 9 shows a zoomed scale for the increases in *Tc* based on increases in wind velocities (1-5 m/s) in this single condition (20°C; 50% relative humidity).

Based on plots from the literature, we see that both *Tc* (Figure 10) as well as heart rate and stroke volume (Figure 11) track closely to observed values during marathon running. Figure 10 shows a comparison of *Tc* outlined by Cheuvront and Haymes (59) and those of the modeling predicitons outlined in our case. Figure 11 shows the pattern of heart rate and stroke volume track to that of the values observed by Billat et al. (60), while being higher based on a higher work rate and more fit individual (Billat et al., showed middle-aged recreational runners).

Additionally, higher resolution can be seen with predicted temperature values based on specific regions or elements of the body (Figure 12).

Figure 4. Core temperature (*Tc*) over time for running a marathon (1,472W) in three environmental conditions

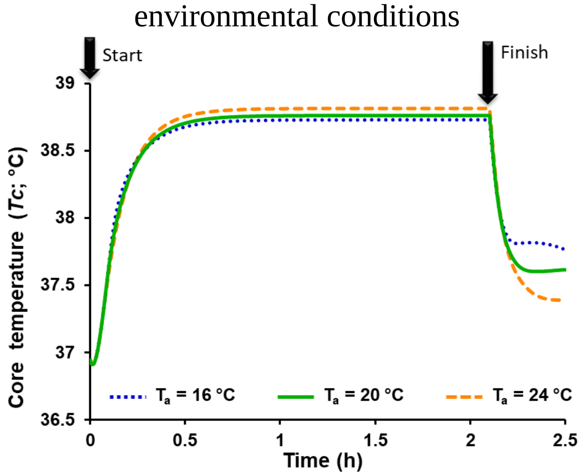


Figure 5. Sweat evaporation rate (kcal/h) over time for running a marathon (1,472W) in three environmental conditions

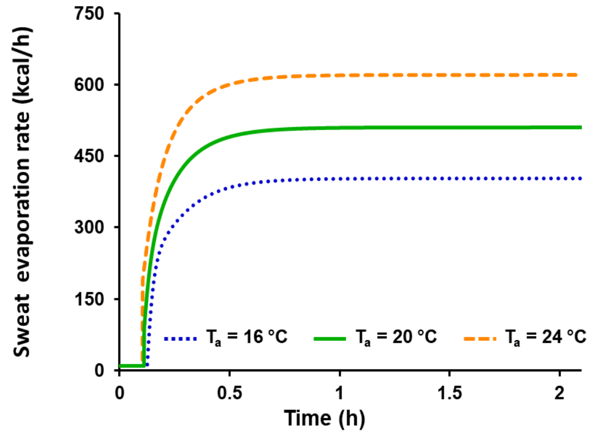


Figure 6. Sweat rate (g/h) over time for running a marathon (1,472W) in three environmental conditions

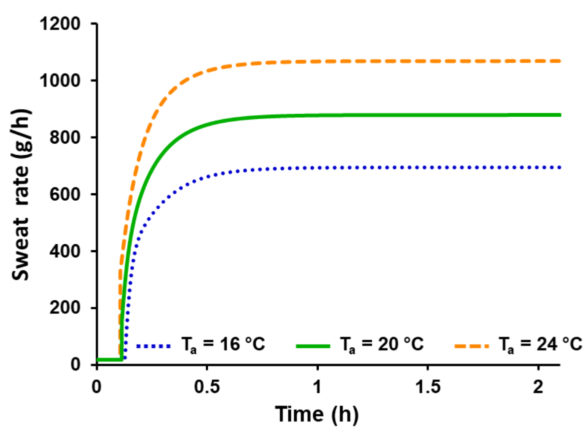


Figure 7. Total body water loss (kg and % body weight) over time for running a marathon (1,472W) in three environmental conditions for approximately 126 minutes

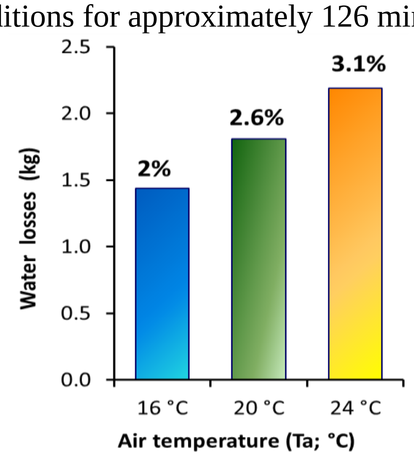


Figure 8. Core temperature (*Tc*) over time for running a marathon (1,472W) (20°C; 50% relative humidity) with two different wind velocities (1 and 4 m/s)

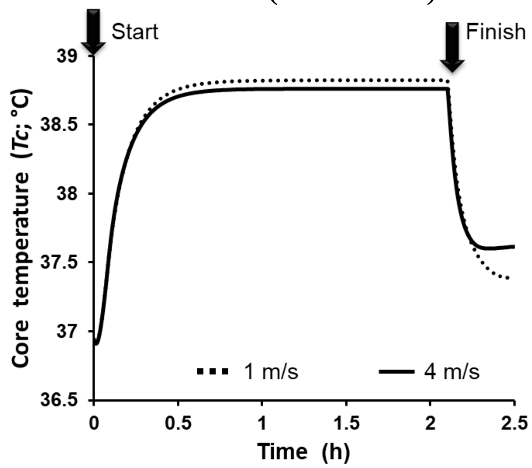


Figure 9. Zoomed scale of core temperature (*Tc*) changes based on running a marathon (1,472W) (20°C; 50% relative humidity) with different wind velocities (1-5 m/s)

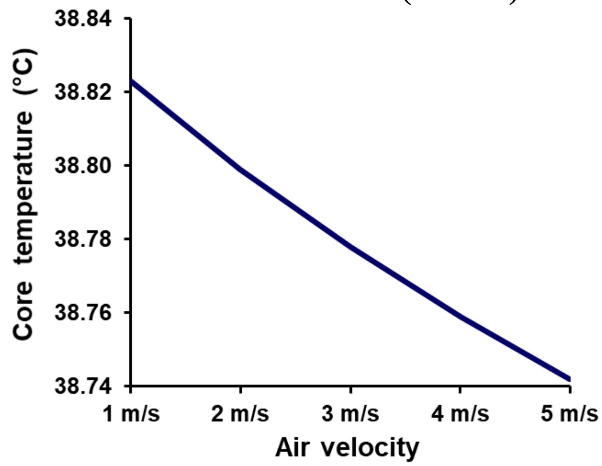


Figure 10. Comparison of modeled core temperature (*Tc*) to those outlined by Cheuvront and Haymes (2001) for running a marathon (20°C; 50% relative humidity)

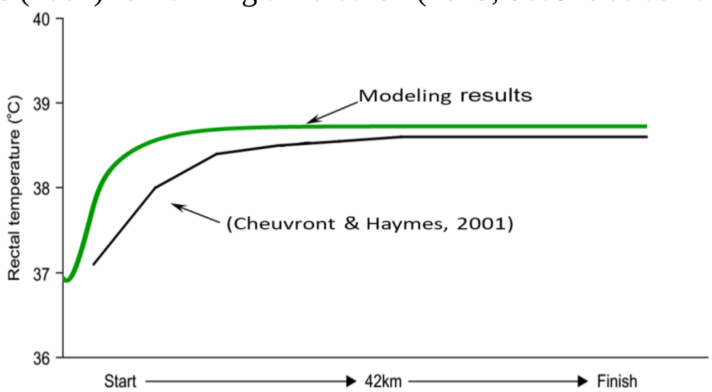


Figure 11. Comparison of modeled and observed heart rate and stroke volume to those from Billat et al., (2012)

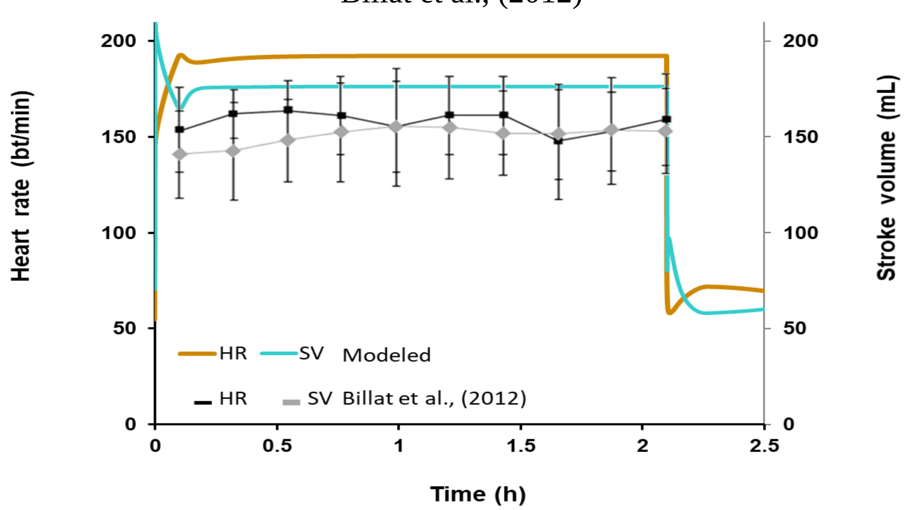
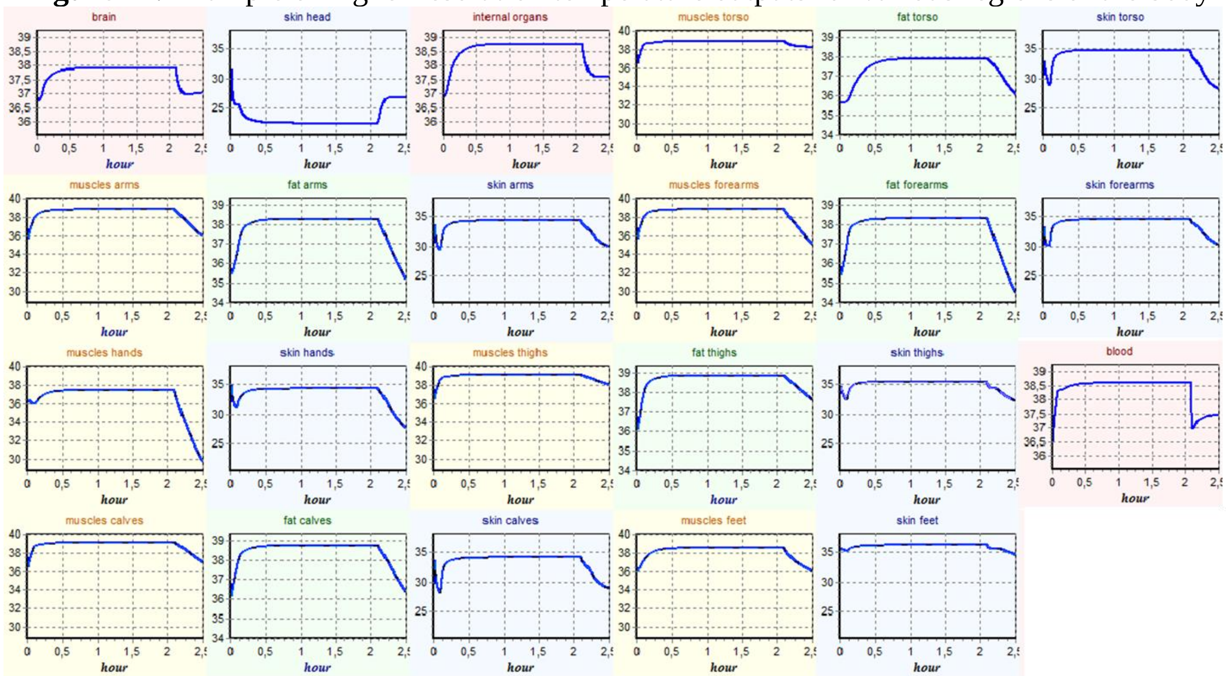


Figure 12. Example of higher resolution temperature outputs for various regions of the body



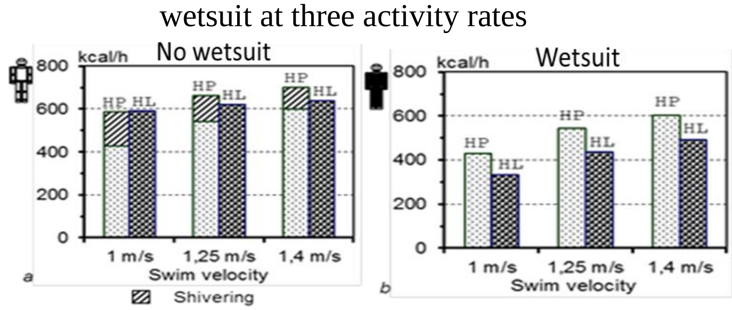
Case of the swimmer in cold water

In the example cases, inputs are based on a healthy and average size man (70 kg; 1.8m^2 body surface area; low body fat 15%), swimming for 30 minutes at three different speeds (1, 1.25, and 1.4 m/s) to correspond to metabolic rates of 500, 630, and 700W (corresponding to 430, 540, and 600 kcal/h). Environmental conditions assumed a water temperature of 14°C and an ambient air temperature of 20°C. Two clothing conditions were modeled, without a wetsuit and with a wetsuit (neoprene, 3mm thick, density of 170 kg/m^3, and thermal resistance of 0.058 m^2·°C/W).

In this case, results show the value in modeling the tradeoffs between clothing conditions (with, without, or with clothing of various characteristics and types). One of the clear differences between these cases can be seen in the balancing of heat; where in the wetsuit condition there is a larger imbalance in heat produced to that lost compared to that predicted in the no wetsuit condition (Figure 13). This specifically demonstrates the value of being able to balance appropriate clothing to activities.

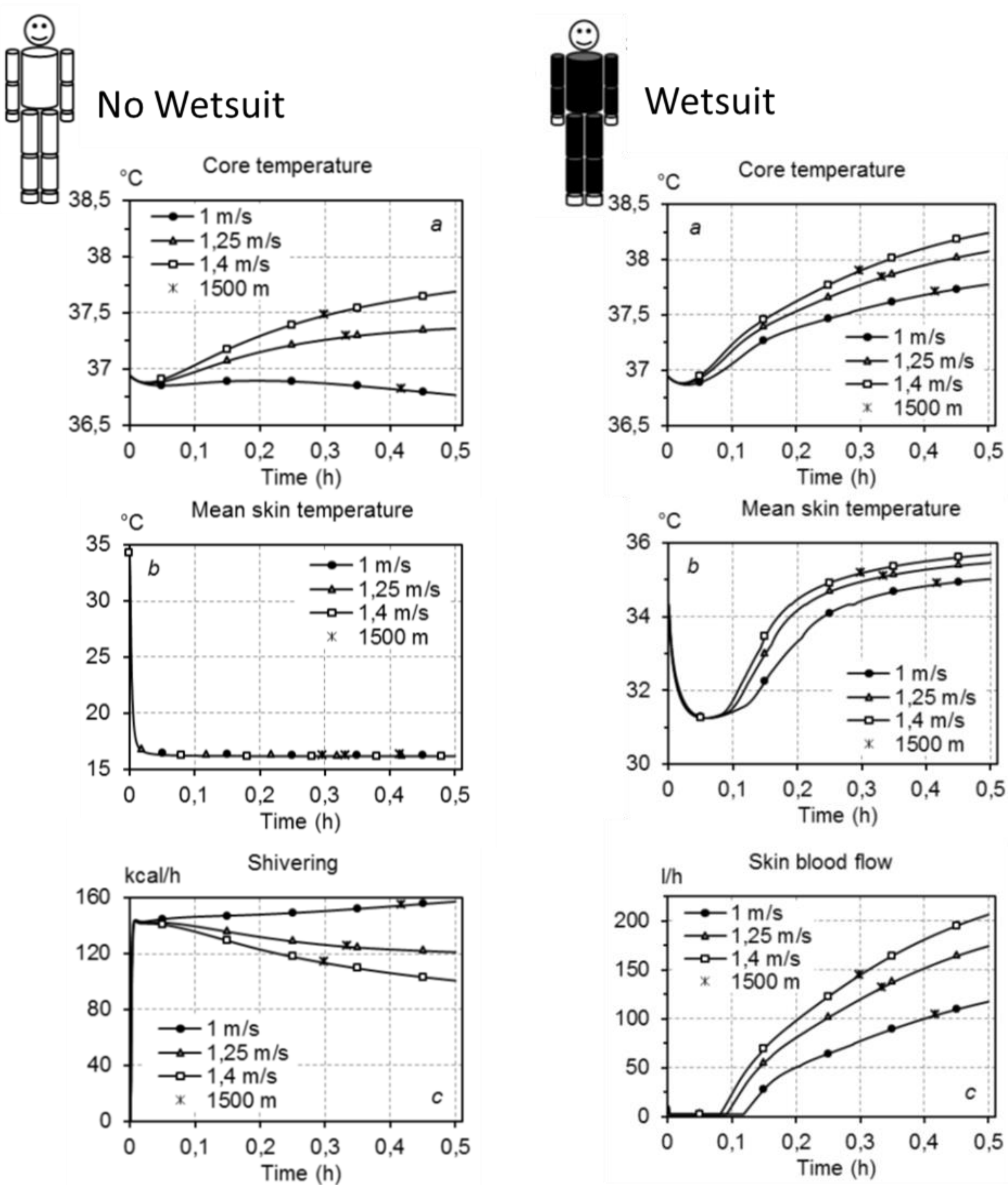
Figure 14 shows the modeled outputs of swimming in the conditions at three different work rates while wearing a wetsuit and without a wetsuit. Of note, differences can be seen between *Tc* and mean *Ts* with differnet work rates and between wetsuit conditions. Additionally, a notable difference is shown where with a wetsuit shivering does not occur, resulting in an increased skin blood flow; while in the no wetsuit condition shiffering occurs and offsets the heat gain on the individual.

Figure 13. Heat balace without and with wetsuit at three activity rates



Note: HP=Heat Production; HL=Heat Loss

Figure 14. Outputs during swimming with and without wetsuit at three different work rates



DISCUSSION

This paper highlights some areas where this type of approach to modeling human thermoregulatory responses can be applied. The case can be made to use thse types of models for predicting potential risks of injury in preparation for activities (e.g., sporting events, occupational work, military activities). Perhaps most helpful in this approach is the ability to model and simulate extreme conditions that otherwise would be unsafe to conduct in regulated activies (e.g., human research studies), but may in fact be conditions expected in real world scenarios. This additional benefit enables opportunities for use in areas such as planning real-world activities (61), research activities, or for potential use in more high risk scenarios such as military planning (62-63) or sporting events (64). Additionally, methods like these have larger future implications specific to climate change and increased risks of thermal injuries (65-69).

The modeling method outlined in this paper has been demonstrated as capable of making predictions of human responses similar to those observed from real data. As a mathematical approach to solving complex interactions between human physiology, environmental conditions, clothing properties, and individual metabolic demands of activities, limitations exist. Future work can be focused on providing individualized effect factors for things such as age differences (70-73), sex differences (74-76), body composition and morphology (77-80), metabolic demands (81-83), dynamic terrains (84-86), and health or fitness elements (87-89).

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"A hungry wolf is stronger than a satisfied dog."

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