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ORIGINAL RESEARCH **OPEN ACCESS**

MODELING THERMOPHYSIOLOGICAL RESPONSES DURING HEAD-IN AND HEAD-OUT WHOLE-BODY WATER IMMERSION

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ABSTRACT

Mathematical representations of humans that are capable of predicting thermophysiological responses provide valuable tools for mitigating health risks during exposures to extreme environments. Humans work or operate in a wide range of conditions, from extreme heat, freezing cold, to partially or fully immersed in water. Each of these conditions presents unique heat exchange relationships that make mathematically modeling responses to each slightly different. **Methods:** A validated mathematical model was used to describe human thermal responses to whole-body water immersion specific to the differences between head-in and head-out conditions. Four different immersion conditions in 17°C water were used (low activity with head out and head in, and moderate activity with head-out and head-in) to describe these responses. **Results:** Modeling showed a moderate increase in shivering rate and water-based convective heat loss that was coupled with significant differences in brain temperature and an observable difference in internal core body temperature during head-in conditions. This work highlights the significance in differences between head-in and head-out during whole-body water immersion.

Dedication:
This work is specifically dedicated to the memory of Dr. Leslie D. Montgomery (1939-2022). His published work on thermoregulatory responses to humans during immersion were of significant importance to advancing this field of science. However, perhaps more notable was his mentorship and dedication to the well-being of others that has helped advance scientists and people generally.

Keywords: thermal modeling, biophysics, immersion, hypothermia

INTRODUCTION

Mathematical models capable of predicting human thermophysiological responses can provide valuable tools for prevention of health risks during exposures to extreme environments. Across the world, humans find themselves working or operating in a wide range of conditions, from ambient air or water exposures, or from extreme heat or cold exposure. For each of these conditions, there are unique heat exchange relationships that make modeling responses to them slightly different.

Mathematically describing the interaction and heat response within these conditions can be simplified by the heat balance equation (Eq. 1). In this equation, we can see a predicted heat rise or fall based on 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:

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

where *M* and *W* represent metabolic heat and from active work rate; *R* is radiation exchange by electromagnetic waves (e.g., solar or infrared); *C* is convective transfer from fluid or vapor contact (e.g., air or water); *K* is conductive transfer from direct contact with solid objects (e.g., a hot or cold surface); and *E* is evaporative heat loss of water from liquid to vapor (e.g., sweat, respiratory water loss).

Several methods and models exist for both hot (1-6) and cold conditions on land (7-10), as well as models specifically tailored to cold or warm water immersion (11-15). During exposure to heat, humans' thermoregulatory system seeks to maintain homeostasis within the environment by focusing on heat dissipation that is mainly achieved by thermolytic function of sweat evaporation; while heat exchange (typically gain) results from each of the remaining pathways (*R*, *C*, *K*) and from metabolic heat production (M+W). During heat stress, the human's thermoregulatory system tends to vasodilate (widening of blood vessels) to allow for maximal blood flow and heat exchange to the skin of the extremities (17-18). In heat stress conditions, the main concern is typically due to heat gain injuries (e.g., hyperthermia, heat stroke, heat exhaustion) (19-21).

In contrast to heat, the thermoregulatory response to cold typically focuses on vasoconstriction (narrowing of blood vessels), to restrict blood flow to the extremities (hands, feet, etc.) to maintain body core temperature to protect major internal organs. By this thermoregulatory response, often cold related heat loss injuries of concern are on the extremities (e.g., frostbite to hands, feet, face) (9, 10).

Water immersion poses an even more potentially extreme and unique challenge, as the conditions limit avenues of heat exchange to almost entirely conduction (22). While several well-known methods exist for specifically modeling immersion (23-27), one of the most crucial improvements was made by Montgomery, who adapted rational coefficients, individual node layers, and a succinct computational framework for scaling human size specific to divers (28-31).

Historically, much of the focus has been on land responses or in cold water immersion. However, climate change poses increasing extremes (32-34), highlighting a less observed exposure that is becoming more relevant is that of warmer water exposure than the thermoneutral point at rest of 35°C water temperature (35-39). While the thermoneutral zone for different work rates during head-in or head-out aquatic activities remains yet unspecified (22).

This manuscript describes human thermophysiological responses to whole-body water immersion specific to the differences between head-in and head-out conditions using a validated mathematical model.

METHOD

Study Design

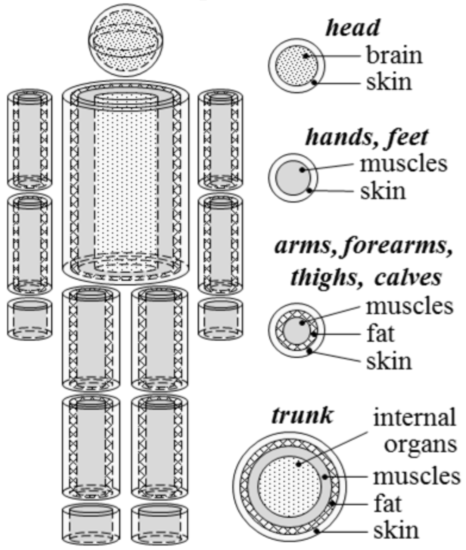
This approach used the Health Risk Prediction Model (HRP) to characterize potential human thermophysiological responses to whole-body water immersion for both head-in and head-out conditions. The HRP is a mathematical model that has been validated for various conditions to include both cold and warm water immersion (15-16, 40-42).

The Health Risk Prediction Model

The Health Risk Prediction (HRP) model is a rationally derived computational model method that makes thermal and physiological predictions (organ, brain, and skin temperatures, sweat rates, blood flow, etc.) based on input scenarios. The HRP method typically divides the human into 14 geometric segments (13 cylinders and one sphere) and 39 compartments (38 layers and a blood compartment) (Figure 1); however, algorithms within the method allow for expansion or simplification of these structures (16).

The HRP model uses a collection of heat balance equations to dynamically account for changes within and between each of the cylinders and layers. Additionally, the HRP includes both a set of passive operating methods to account for heat exchange between layers as well as a set of active calculations to account for physiological responses such as shivering, sweating, and blood flow.

Figure 1. Health Risk Prediction (HRP) model human divided into 14 segments (13 cylinders and one sphere) and a blood compartment)



Analyses

To demonstrate the predicted human responses graphically, the HRP method was used to mathematically model conditions similar to those experimented by Pretorius et al., (43, 44). Specific inputs to the model included a normally hydrated and relatively healthy male of typical size (~1.72 m^2), in two immersion statuses (one with head-out of the water and one with head-in and fully immersed). Two work rates were used for both conditions (120 and 275 kcal/h), water temperature was set to 17°C, and external conditions were set to an air temperature of 22°C, relative humidity of 50%, and air velocity of 0.1 m/s (Table 1).

Table 1. Experimental conditions

	Low activity	*Moderate activity*
Metabolic rate	120 kcal/h	275 kcal/h
Water temperature	17°C	17°C
Air temperature	22°C	22°C
Relative humidity	50%	50%
Air velocity	0.1 m/s	0.1 m/s
Clothing	Nude	Nude

RESULTS

Predicted modeling outputs for each of the four conditions included graphical comparisons of brain, internal organ core, and skin temperatures (T_B, T_C, T_{SK}; °C), shivering metabolic rate (kcal/h), and water convection (kcal/h). For both the low (120 kcal/h) and moderate (275 kcal/h) conditions, comparisons were made between the two immersion states of head-in and head-out.

Figures 2 and 3 show T_B and T_C for both metabolic work rates, low (a panels) and moderate (b panels). From these two sets of figures, a drastic lowering of T_B is observed for the head-in versus head-out (Figure 2); while there is a slightly higher internal T_C for head-in compared to head-out conditions (Figure 3). Additionally, while the temperatures themselves adjust to the conditions, these patterns of higher and lower remain relatively consistent between the two work rates.

Figure 2. Brain temperatures (T_B; °C) for both low (a) and moderate (b) work rates for head-out (red lines) and head-in (blue lines).

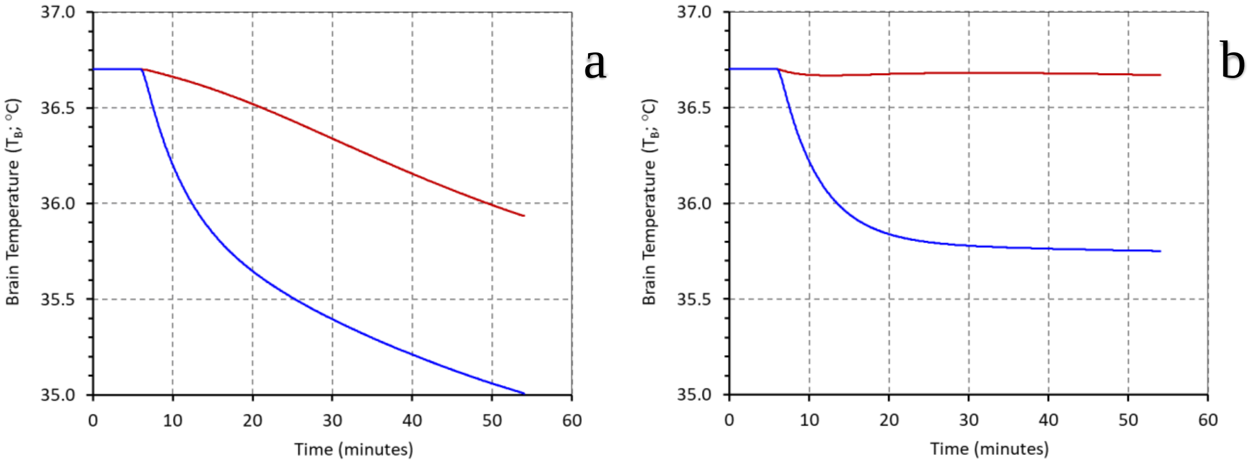
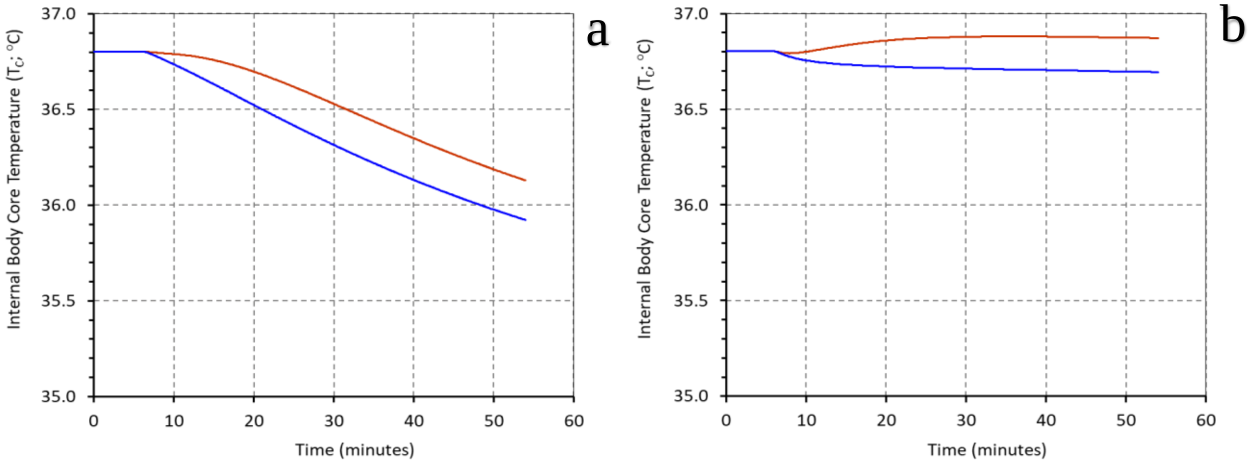


Figure 3. Internal organ body core temperatures (T_C; °C) for both low (a) and moderate (b) work rates for head-out (red lines) and head-in (blue lines).



The predictions from Figure 3 show a similar T_C pattern to that of the work by Pretorius et al., (43, 44). Given the modeling approach balances the whole humans' heat exchange, this similar response of T_C allows us to reasonably assume the T_B responses shown in the Figure 2 were valid.

Figure 4 shows T_{SK} for both metabolic work rates and immersion statuses. From this figure, there is an expected observation of differences between the immersion statuses, but a similarity between the two work rates.

Figure 4. Skin temperatures (T_{SK}; °C) for both head-out low activity (solid red line), head-in low activity (solid blue line) and head-out moderate activity (dashed red line) and head-in moderate activity (dashed blue line).

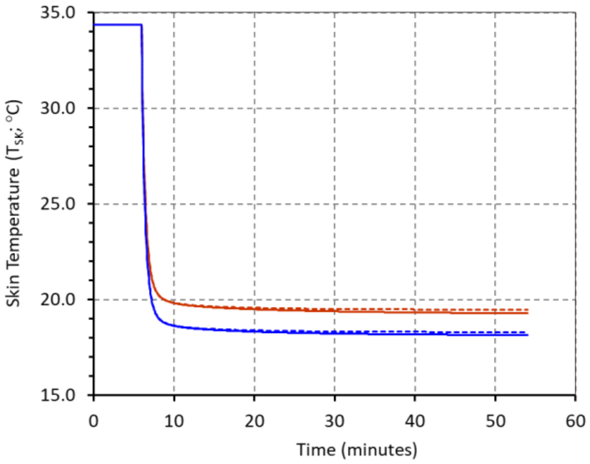
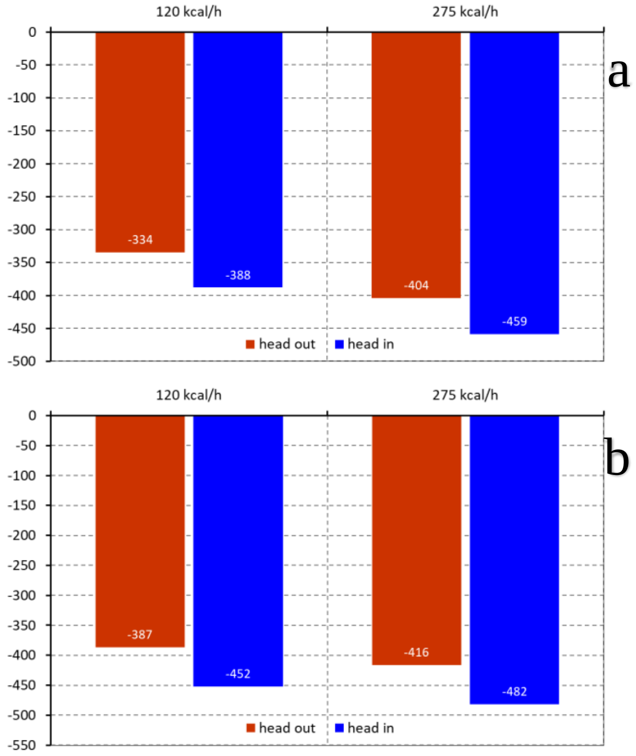


Figure 5 shows convective heat loss across each of the four conditions at both the end of the scenario (a) and for the average of the entire event (b). From this, there is clearly a higher collective heat loss observed during the head-in immersion at both the end of the event (panel a) and for the average across all time points (panel b).

Figure 6 shows shivering metabolic rate for both the low and moderate activity conditions. Figure 6 shows that shivering metabolic heat produced during head-in conditions were much higher than compared to those of head-out. From this figure, an observed higher rate of shivering is predicted in both the low and moderate work rates during head-in immersion. This point coupled with data shown in Figures 2 and 3 is important, as it shows both an increased metabolic demand due to shivering (Figure 6) as well as an associated lowering of both T_B and T_C (Figures 2 and 3, respectively).

Figure 5. Water based convective heat loss (kcal/h) for head-out (red boxes) and head-in (blue boxes) for the end of the scenario (a) and for the average across the entire event.



Similar to the comparable T_{SK} values across conditions, modeling showed several elements to be closely related to each other. Figure 7 demonstrates the relatively direct relationship between T_C and body blood temperature (T_{BL}).

Figure 6. Shivering (kcal/h) for both low (a) and moderate (b) work rates for head-out (red lines) and head-in (blue lines).

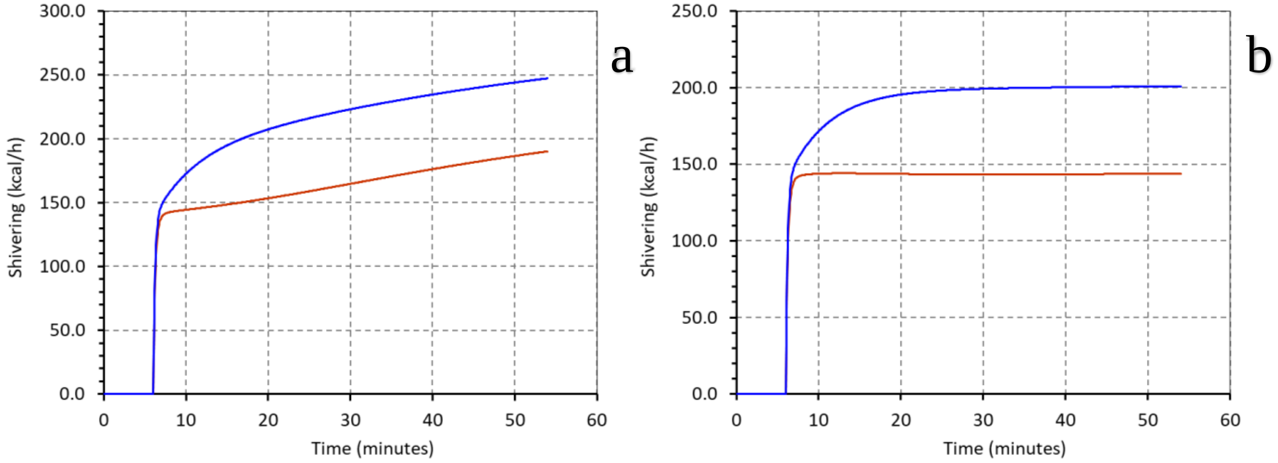
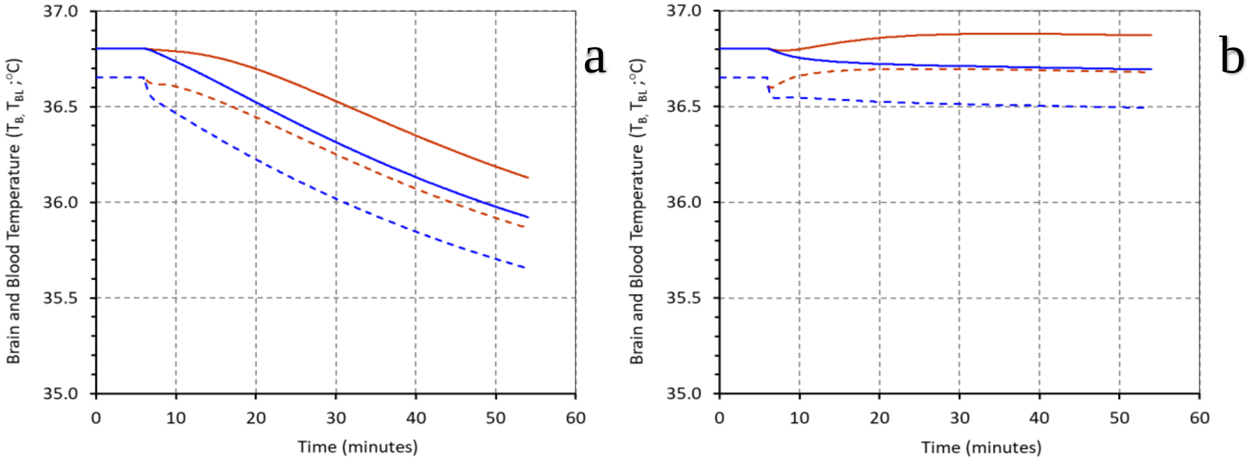


Figure 7. Overlay of blood temperature (T_{BL}) (solid lines) and body core temperature (T_C) (dashed lines) for both low (a) and moderate (b) work rates for head-out (red lines) and head-in (blue lines).



DISCUSSION

This work demonstrates the important significance between differences in head-out versus head-in during whole-body immersion. Additionally, this manuscript demonstrates how sophisticated mathematical models can be used to describe complex physiological interactions with extreme environmental conditions. The present analyses predicted responses that were in agreement with those observed in the collective laboratory data. The HRP acceptable predictions strengthen the hypothesis for an extension of confidence in the validity of other more difficult to obtain measures such as brain temperature (T_B). Nonetheless, brain temperature is measured to manage neurological emergencies (e.g., recovery from brain damage) in hospital settings. Advances in new technologies of implantable and biodegradable brain temperature sensors may allow for further examination of the accuracy of biophysical models in field conditions (45).

Predictive data from HRP model as depicted in Figures 2 and 3 are consistent with previous studies, using heat flux method to estimate head heat loss, evidencing that T_B is much more sensitive to water immersion duration and water temperature than that of T_C during exercise in cold water (43-44, 46). A moderate workload may attenuate the declined trend of intracranial temperature inducing its stabilization for the first hour in contrast to a light intensity activity. A possible explanation for the increased rate of brain cooling in head-in compared to head-out condition is the augmented exposed surface area, e.g., whole-head immersed (conductive heat loss), blood cooling redistribution between brain and core body (convective heat loss), and the insufficient amount of total heat energy production (shivering, and mechanical workload) (46). While this seems somewhat intuitive once stated; it is a difficult point to demonstrate without models such as this. Similarly, Figure 4 demonstrates how closely related skin temperature becomes to that of the water temperature due to the overwhelming conductive relationship.

Similar to many comprehensive modeling methods, it is possible that improvements can be found that optimize predictive accuracy in different conditions (especially for elements more difficult to measure). For example, estimates of metabolic costs, shivering responses, or sweat rates can each have significant impacts to the modeling outputs, and each have many different approaches (9-10, 47-51). Another element for consideration is the effects of different clothing types on heat exchange, or more pointedly for this manuscript, thermal insulation during immersion status.

Future work in this area can be focused on expansion to more comprehensive modeling methods (e.g., finite element models) (52-54), assessing improvements related to individual differences (e.g., age, sex, body composition, morphology) (55-65). While special attention can then be made to account for unique interventions and how they relate to a person's health and performance (e.g., medications, prior nutrition, or supplement uses) (66-74), fitness levels (75-78), or existing comorbidities (69, 79-82) to expand use to the broader population.

An additional element worth noting is the complexity of the interacting effects of each of the variables within a real-world scenario. That is to say, there is a complicated balance between each element of heat production and heat loss. For example, generally metabolic heat production is the main factor to consider, as it can outweigh or offset the impact of heat loss (e.g., a person can move more and remain warm in a cold environment). However, in immersed conditions, the restriction of other avenues of heat exchange and a near sole reliance on convection makes correctly calculating this rate even more critical to accurate predictions. This point can be made quantitatively by looking at the similarities between elements such as predictions of skin temperature (T_{SK}) across work rates (i.e., Figure 4) or the pattern similarities between blood temperature (T_{BL}) and body core temperature (T_C) (i.e., Figure 7).

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

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