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QUANTITATIVE ASSESSMENT OF THE MEANINGFUL DIFFERENCES IN EVAPORATIVE POTENTIAL

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14. ABSTRACT

This paper demonstrates a novel approach in human thermoregulatory modeling. A male torso model was created from medical image data. This allowed for accurate geometry of the organs to be used when modeling thermoregulation. Thermoregulation was simulated through heat transfer using finite element analysis. The thermoregulatory activities consisted of vasodilation, vasoconstriction, sweating, and shivering. They all work together to attempt to create heat balance within the body.

The simulations show that temperature profiles and thermoregulatory responses can be predicted based on given the environmental conditions. In warm ambient temperatures, sweating and vasodilation occur in an attempt to exacerbate heat loss, while in cold ambient temperatures, shivering occurs to generate more heat and vasoconstriction occurs to lessen heat loss. The paths of the rectal and heart/esophageal temperatures compared well with similar temperatures recorded during previous studies, but the temperatures sometimes deviate significantly.

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EXECUTIVE SUMMARY

Introduction: Measures of thermal and evaporative resistance (R_t and R_{et}) are often used in combination with thermoregulatory models to predict heat stress and as a measure to compare clothing performance. For the US Army, these values are most commonly converted to units of clo (thermal insulation, 1 clo = 0.155 $m^2 \cdot °C \cdot W^{-1}$) and i_m (moisture permeability index, N.D.) and combined to create a ratio of the two; i_m/clo (evaporative potential). Traditionally, when comparing modeled performance of ensembles, only values of ≥ 0.1 i_m/clo have been considered significant. The purpose of this study is to examine, quantitatively, how valid this threshold value is. **Methods:** Using a biophysics-based thermoregulatory model, core body temperature rise was predicted over 120 minutes; where input conditions were controlled for three environmental conditions (warm, hot-humid, and hot-dry), a standard individual (healthy, acclimated, standard male: 172 cm, 70 Kg), set activity rate (350 W). Clothing insulation was held constant at 1.83 clo, but the value for i_m/clo was increased incrementally by 0.1, from 0.5 to 0.45. **Results:** Using a notional limit of a predicted core temperature of 38.5 °C, each of the levels of i_m/clo was modeled. The incremental improvements in evaporative potential by 0.1 i_m/clo resulted in predicted increases in safe work times / tolerance time to reach this 38.5 °C, by 7.7 ± 3.8, 17.0 ± 9.6, 30.7 ± 18.7, and 50.3 ± 35.6 minutes or by 13 ± 6, 28 ± 14, 52 ± 28, and 84 ± 54% increases respectively. The pattern of these modeled impacts was consistent across varied environments; while the exact time effects either narrowed in extreme conditions (e.g., high humidity, high heat) or broadened (e.g., low humidity conditions). **Discussion:** This modelling work provides evidence to support the use of a value of ≥ 0.1 i_m/clo as a lower limit for guidance in describing significant differences in ensemble performance related to thermal outcomes. However, it remains important to conduct comprehensive comparisons as to the meaning behind these differences in the context of anticipated use cases and environmental conditions and to properly design human research studies with conditions that ensure observable and significant physiological differences.

INTRODUCTION

Measures of thermal and evaporative resistance (R_t and R_{et}) are often used in combination with thermoregulatory models to predict heat stress and as a measure to compare clothing performance. These measures are collected using sweating thermal manikins in controlled climate conditions set to industry standards by the American Society of Testing and Materials (ASTM) [1-2]. For the US Army, these values are most commonly converted to units of clo (thermal insulation, 1 clo = 0.155 m^2 •°C•W^{-1}) and i_m (moisture permeability index, N.D.) and combined to create a ratio of the two; i_m/clo (evaporative potential) [3-4].

The set of standard tests and conversion methods are:

$$R_t = \frac{(T_s - T_a)}{Q/A} [\mathrm{m^2K/W}] \qquad \text{Eq 1.}$$

Thermal resistance (R_t) is the dry heat transfer from the surface of the manikin through the clothing and into the environment, mainly from convection; where T_s is surface temperature, T_a is the air temperature in °C or °K; Q is power input (W) to maintain the surface (skin) temperature (T_s) of the manikin at a given set point; A is the surface area of the measurement in m^2.

$$1\ clo\ =\ 6.45(I_T) \qquad \text{Eq 2.}$$

Measures of R_t can then be converted to units of clo, where I_T is the total insulation including boundary air layers.

$$R_{et} = \frac{(P_{sat} - P_a)}{Q/A} [\mathrm{m^2Pa/W}] \qquad \text{Eq 3.}$$

Evaporative resistance (R_{et}) is heat loss from the body in isothermal conditions ($T_s \approx T_a$); where P_{sat} is vapor pressure in Pascal at the surface of the manikin (assumed to be fully saturated), and P_a is vapor pressure, in Pascal, of the chamber environment.

$$i_m = \frac{60.6515 \frac{Pa}{°C} R_t}{R_{et}} \qquad \text{Eq 4.}$$

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.

Traditionally, when comparing modeled performance of ensembles, only values of ≥ 0.1 i_m/clo have been considered significant. The purpose of this study is to examine, quantitatively, how valid this threshold value is.

METHODS

A biophysics-based thermoregulatory method [5] was used to model rise in core body temperature over 120 minutes for five levels of i_m/clo within three environmental conditions. The modeled results of these simulated responses were compared based on physical time in minutes to reach predicted core temperatures of 38.5 °C and as a percentage change from i_m/clo level-to-level. The model used included inputs to individual, activity level, environment, and clothing biophysical values. Modeled scenarios held input regarding the individual and activity level constant; while changing environment and clothing input variables.

Modeling inputs

Individual and Activity Level

All scenarios modeling inputs assumed a healthy, acclimatized (12 days), 'standard man' (height: 172 cm, mass: 70 Kg) working at an activity level of 350 W.

Environment

The environmental inputs included values of ambient temperature (Ta, °C), relative humidity (RH, %), and wind velocity (V, m/s). Three distinct conditions were modeled: Warm (35 °C, 30 % RH, 1 m/s), Hot-Humid (35 °C, 60 % RH, 1 m/s), and Hot-Dry (48 °C, 20 % RH, 1 m/s).

Clothing biophysics

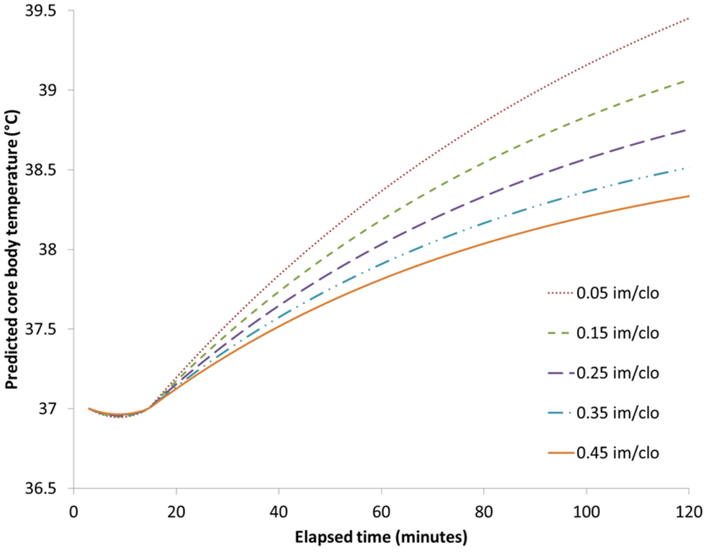
The total insulation (I_T) was held constant; while the i_m/clo values were modified to five different levels: 0.05, 0.15, 0.25, 0.35, and 0.45.

RESULTS

Using a notional limit of 38.5 °C for predicted core temperature, each of the levels of i_m/clo was plotted based on the three environmental conditions (Figures 1-3). Figure 1 outlines results of temperate conditions, showing increases of 0.1 im/clo (i.e., improved evaporative potential) starting at 0.05 i_m/clo, result in predicted increases in time to reach the upper limit for safe work, a core temperature of 38.5 °C; by 12, 16, 24, and 39 minutes or 19%, 44%, 83%, and 144% respectively. This can also be viewed by decreases starting at 0.45 i_m/clo reducing by 0.1 as 25%, 41%, 51%, and 59% reductions in minutes to reach this limit of 38.5 °C.

The pattern of these modeled impacts remains similar across varied environments, such as jungle or desert conditions (e.g., hot-humid and hot-dry) as can be seen in Figures 2 and 3. Similar time effects can be seen related to extremes of the environment, e.g., narrowed response in high humid conditions or higher metabolic demand activities or broader response in temperate conditions, lower metabolic rate activities.

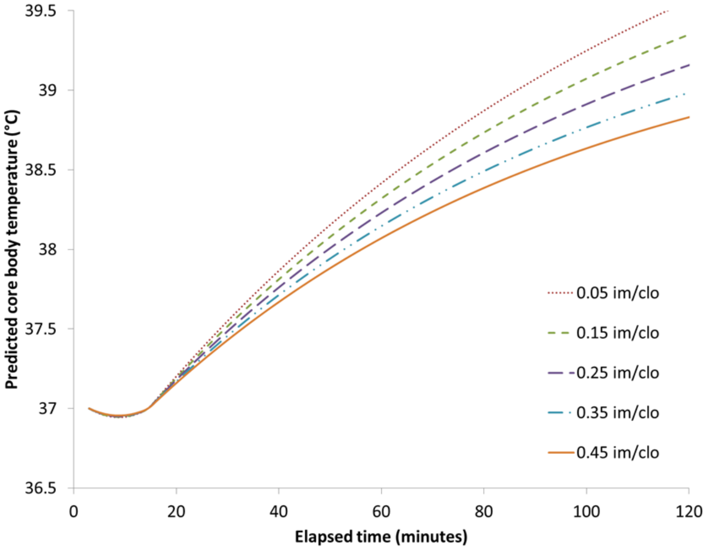
Figure 1: Predicted rise in core body temperature (Tc) over time (minutes) based on clothing evaporative potential (i_m/clo) levels – Warm (35 °C, 30 % RH, 1 m/s wind velocity)



Time (minutes) to reach 38.5°C by i_m/clo in Warm Conditions

		% increase				
im/clo	time to 38.5	0.05	0.15	0.25	0.35	0.45
0.05	63	0%	19%	44%	83%	144%
0.15	75	-16%	0%	21%	53%	105%
0.25	91	-31%	-18%	0%	26%	69%
0.35	115	-45%	-35%	-21%	0%	34%
0.45	154	-59%	-51%	-41%	-25%	0%

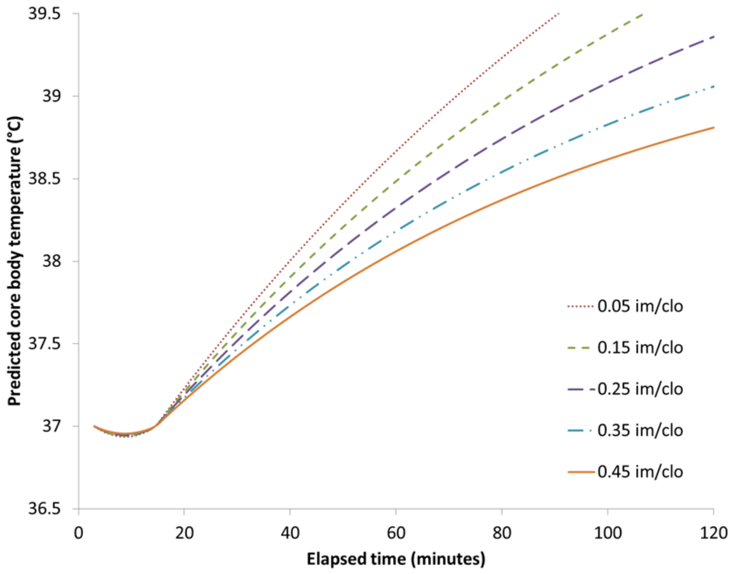
Figure 2: Predicted rise in core body temperature (Tc) over time (minutes) based on clothing evaporative potential (i_m/clo) levels – Hot-Humid (35 °C, 60 % RH, 1 m/s wind velocity)



Time (minutes) to reach 38.5°C by i_m/clo in Hot-Humid Conditions

		% increase				
im/clo	time to 38.5	0.05	0.15	0.25	0.35	0.45
0.05	52	0%	12%	25%	44%	67%
0.15	58	-10%	0%	12%	29%	50%
0.25	65	-20%	-11%	0%	15%	34%
0.35	75	-31%	-23%	-13%	0%	16%
0.45	87	-40%	-33%	-25%	-14%	0%

Figure 3: Predicted rise in core body temperature (Tc) over time (minutes) based on clothing evaporative potential (i_m/clo) levels – Hot-Dry (48 °C, 20 % RH, 1 m/s wind velocity)



Time (minutes) to reach 38.5°C by i_m/clo in Hot-Dry Conditions

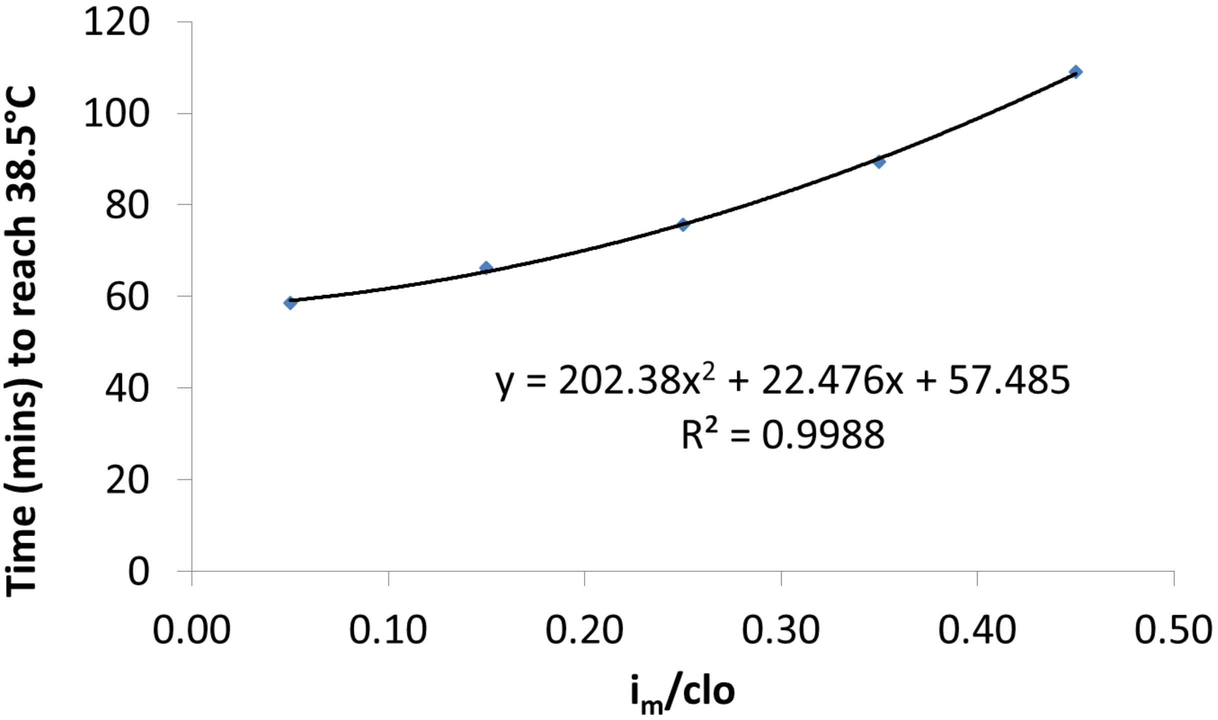
		% increase				
im/clo	time to 38.5	0.05	0.15	0.25	0.35	0.45
0.05	61	0%	8%	16%	28%	41%
0.15	66	-8%	0%	8%	18%	30%
0.25	71	-14%	-7%	0%	10%	21%
0.35	78	-22%	-15%	-9%	0%	10%
0.45	86	-29%	-23%	-17%	-9%	0%

When averaged across the different environments, the time to reach 38.5 °C and rate of change maintains a consistent pattern (Table 1). These aggregated averages were used to create a fitted polynomial curve and associated equation (Eq 5) that can be used to estimate the impact of increases or decreases in i_m/clo values on safe work limits within the outlined constraints (i.e., standard man parameters, work rate of 350 W); where *y* (time in minutes) to reach 38.5 °C is factored based on *x* (i_m/clo) (Figure 4).

Table 1. Average time (minutes) to reach 38.5 °C by i_m/clo across environmental conditions

		% increase				
im/clo	time to 38.5	0.05	0.15	0.25	0.35	0.45
0.05	59		13%	29%	52%	84%
0.15	66	-11%		14%	34%	62%
0.25	76	-22%	-12%		17%	41%
0.35	89	-33%	-24%	-14%		20%
0.45	109	-43%	-36%	-28%	-16%	

Figure 4: Average time (minutes) to reach a core body temperatures of 38.5°C by i_m/clo across environmental conditions with a starting core temperature of 37°C



Equation 5 $Time\ to\ 38.5\ °\mathrm{C} = 202.38 \cdot i_m/clo^2 + 22.476 \cdot i_m/clo + 57.485\ \ [R^2 = 0.998]$

DISCUSSION

This work provides evidence to support the use of a value of ≥ 0.1 i_m/clo as a threshold for guidance in describing significant differences in ensemble performance related to thermophysiological outcomes. However, it still remains important to conduct comprehensive comparisons as to the meaning behind these differences in the context of anticipated use cases and environmental conditions and to properly design human research studies with conditions that ensure observable and significant physiological differences.

While this approach is helpful, it is still important to investigate the underlying causes of these differences to determine how those results may change with each factor. Revisiting past results and interpretations based on these results is especially important in the context of anticipated use cases and environmental conditions which differ significantly from those described in this report. Modeling exercises like this one can help guide the proper design of human research studies with conditions that will ensure observable and significant physiological differences.

Given the variability in human responses, it is important to note some of the values that were held constant for this analysis. While the overall findings should remain consistent, it is important to note that changes to the baseline simulated human inputs will result in different modeled outcomes [6-10].

Constants made in the model:

- Standard male (172 cm, 70 kg), acclimatized ≥ 12 days, normally hydrated
- Work rate of 350 W
- Constant total insulation (I_T) clo value of 1.83
- Constant wind speed coefficients for both clo (-0.22) and i_m/clo (0.28)

An additional point to mention is that as i_m/clo takes into account the ratio of both clo and i_m, varying only the i_m/clo essentially makes a change directly to the i_m input; while in the calculation for the i_m index takes into account the measured value of the both thermal and evaporative resistances (R_t and R_{et}) (Eq 4). Due to this relationship it is also important to note that this work outlines theoretical modeling versus practical changes that would likely be observed.

Due to the high degree of repeatability of test measurements, almost all differences between ensembles are statistically significant, but based on ASTM guidance [1-2], any difference between means <10% is unlikely to have a meaningful effect on clothing performance. Repeatability of manikin results, which results in a small SD for each test item, using conventional statistics, the differences between ensembles that have use similar textiles and designs are almost always statistically significantly different, even for very small sample sizes (N=3), but demonstrate virtually no significant differences in performance. Therefore, the ±10% rule for R_t is pragmatic response to that statistical anomaly.

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