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METHOD FOR ESTIMATING EVAPORATIVE POTENTIAL (IM/CLO) FROM ASTM STANDARD SINGLE WIND VELOCITY MEASURES

United States Army
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14. ABSTRACT

Three key biophysical parameters of interest when modeling thermoregulatory responses include: thermal resistance (Rct), evaporative resistance (Ret), and wind coefficients (g) specific to each resistance. Using a thermal sweating manikin, biophysical properties (Rct and Ret) were measured on 65 different clothing ensembles. A stepwise forward adding linear regression method was used to create an estimation equation (n = 20); where standard 0.4 m/s measures of im/clo can be converted to modeling inputs at 1 m/s: im/clo(1.48) – 0.04 (R2 = 0.998). Root mean squared error (RMSE) and mean absolute error (MAE) of a verification dataset (n = 45), showed close agreement of the estimated and actual measured values of im/clo at 1 m/s, RMSE = 0.013 and MAE = 0.009. This report describes the mathematical methods for estimating the biophysical inputs needed for thermoregulatory modeling using only the data provided by standardized test methods. This method enables use of standard collected data, American Society of Testing and Materials International (ASTM) method, for modeling purposes that previously required additional testing.

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EXECUTIVE SUMMARY

Modeling clothing effects on thermoregulation in humans at various physical activity levels and environmental conditions requires knowledge of the biophysical measurements of specific clothing being worn. Three key biophysical parameters of interest when modeling thermoregulatory responses include: thermal resistance (R_{ct}), evaporative resistance (R_{et}), and wind coefficients (^{g}) specific to each resistance.

Using a thermal sweating manikin, biophysical properties (R_{ct} and R_{et}) were measured on 65 different clothing ensembles. Using a subset of 20 ensembles, a linear regression equation was developed to estimate the change in evaporative potential (i_m/clo) from standard measures at 0.4 m/s to estimate i_m/clo at 1 m/s, values currently used for thermoregulatory modeling.

A stepwise forward adding linear regression method was used to create an estimation equation; where standard 0.4 m/s measures of i_m/clo can be converted to modeling inputs at 1 m/s: i_m/clo(1.48) – 0.04 ($R^2 = 0.998$). Statistical tests of root mean squared error (RMSE) and mean absolute error (MAE) were applied to a verification dataset (n = 45), showing close agreement of the estimated and actual measured values of i_m/clo at 1 m/s, RMSE = 0.013 and MAE = 0.009.

This report describes the mathematical methods for estimating the biophysical inputs needed for thermoregulatory modeling using only the data provided by standardized test methods. This method enables use of standard collected data, according to American Society of Testing and Materials International (ASTM), for modeling purposes that previously required additional testing.

INTRODUCTION

Sweating thermal manikins have long been used to provide biophysical measures of clothing and equipment worn by the human [1]. These measures can be used to estimate the level of imposed thermal stress (hot environment) or thermal protection (cold environment) provided by the ensemble. While direct biophysical comparisons can be helpful, i.e., comparing one ensemble's value to another [2], a more informative approach is to combine these measured values with thermoregulatory models. These models enable predictions of thermoregulatory responses based on different individuals, as well as varied environments, clothing, or activity levels.

The current standard for testing using sweating thermal manikins calls for two fundamental measures at a single wind velocity of 0.4 m/s (0.89 mph). The American Society of Testing and Materials International (ASTM) have two defined standards for testing both thermal resistance (R_{ct}) [3] and evaporative resistance (R_{et}) [4]. These two measures represent the dry heat exchange (R_{ct}: convection, conduction, and radiation) and wet heat exchange (R_{et}: evaporation). After converting both R_{ct} and R_{et} into units of clo and i_m [5, 6], a ratio can be used to describe an ensemble's evaporative potential (i_m/clo) [7].

Thermal resistance (R_{ct}) is the dry heat transfer from the surface of the manikin through the clothing and into the environment, mainly from convection, described as:

$$R_{ct} = \frac{(T_s - T_a)}{Q/A}\,[\mathrm{m^2K/W}]$$

where T_s is surface temperature and T_a is the air temperature, both 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. These measures of R_{ct} can then be converted to units of clo:

$$1\,clo \;=\; 6.45(I_T)$$

where I_T is the total insulation including boundary air layers. Evaporative resistance (R_{et}) is heat loss from the body in isothermal conditions ($T_s \approx T_a$), described as:

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

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 Pascals, of the chamber environment. 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 defined as:

$$i_m = \frac{60.6515 \frac{Pa}{°C} R_{ct}}{R_{et}}$$

In order to use the biophysical measures of clo and i_m for thermoregulatory modeling there is typically a need to first estimate the effects of wind velocity on the ensemble's biophysical characteristics (i.e., how changes in wind affect clo and i_m values). These effects are typically referred to as wind velocity coefficients or gamma values (^{g}) [8]. Historically, obtaining these coefficients consisted of collecting measurements of both R_{ct} and R_{et} at multiple wind velocities, above the ASTM standard of 0.4 m/s. However, recent work suggests estimating these coefficient values can be estimated from single wind velocity tests [8].

Clothing properties and wind coefficients are critical inputs to predictive mathematical models such as the Heat Strain Decision Aid (HSDA) [9, 10], or SCENARIO [11]. These models, by design, predict human thermoregulatory responses to various environmental conditions and therefore require quantitative insights into the change in clothing properties with changes in wind velocity. These mathematical models have been used to help guide military activities [12, 13, 14] and healthcare responders [15], and in post hoc analyses that resulted in improved clothing [16, 17]. For these reasons, the ability to model the effects of wind velocity on the biophysical properties of clothing is of significant interest to modelers, researchers, physiologists, and clothing developers.

This report 1) describes biophysical properties of a wide range of clothing ensembles, 2) describes a method for estimating the biophysical inputs (clo and i_m) needed for thermophysiological modeling using only measurements at a single standard wind velocity, and 3) demonstrates the validity of this method using a large dataset of ensemble biophysical characteristics.

METHODS

Biophysical properties (R_{ct} and R_{et}) of 65 clothing ensembles of different physical characteristics were measured. These ensembles ranged from physical fitness clothing (shorts, t-shirt, socks, and sneakers), to fully encapsulating personal protective ensembles (PPE) and explosive ordnance disposal (EOD) suits.

Each ensemble was tested to ASTM standards for "dry" thermal resistance (R_{ct}) (ASTM F1291-10) [3] and "wet" evaporative resistance (R_{et}) (ASTM F2370-10) [4], each at the prescribed wind velocity conditions of 0.4 m/s. To enable a ground truth calculation of a wind coefficient, following the standard measures at 0.4 m/s each ensemble was tested at two additional wind velocities.

Statistical Analysis

Statistical analyses were performed using SAS 9.3 Statistical Software (SAS Institute Inc., Cary, NC). A forward adding stepwise multiple linear regression modeling method was used to develop an i_m/clo estimation equation from a model dataset (n =

20) (Table 1). The regression model developed from the model dataset was applied to a verification dataset (n = 45) (Table 2). The accuracy of the estimation method was then assessed using root mean square error (RMSE) and mean absolute error (MAE), comparing the predictions to the measured data. The equations for RMSE and MAE:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n} |e_i|$$

where d_i is the difference between observed and predicted i_m/clo for each ensemble, and n is the number of data points. The MAE being the average of the absolute errors within the predictions, in the equation: where f_i is the predicted value, y_i is the actual value, and e_i is the absolute error.

Tables 1 and 2 present the measured biophysical values to ASTM standards (0.4 m/s wind velocity) and for measured values at 1 m/s conditions. The biophysical data from 20 ensembles (Table 1) were used to create the model. The data in Table 2 from 45 ensembles were used to validate the model.

Table 1. Biophysics data used for model development (n = 20)

Ensemble	***0.4 m/s*** **clo**	***0.4 m/s*** **i_m**	***0.4 m/s*** **i_m/clo**	***1 m/s*** **clo**	***1 m/s*** **i_m**	***1 m/s*** **i_m/clo**
1	1.368	0.410	0.276	1.092	0.410	0.377
2	1.566	0.401	0.246	1.230	0.401	0.327
3	1.586	0.391	0.246	1.247	0.391	0.316
4	1.619	0.396	0.245	1.290	0.396	0.308
5	1.578	0.385	0.238	1.243	0.385	0.311
6	1.574	0.382	0.237	1.248	0.382	0.306
7	1.577	0.383	0.236	1.251	0.383	0.306
8	1.583	0.363	0.217	1.261	0.363	0.283
9	1.603	0.358	0.223	1.290	0.358	0.278
10	1.632	0.350	0.217	1.283	0.350	0.270
11	1.529	0.374	0.223	1.202	0.374	0.311
12	0.877	0.467	0.536	0.646	0.478	0.742
13	0.910	0.462	0.507	0.652	0.476	0.730
14	0.909	0.473	0.528	0.652	0.478	0.738
15	0.919	0.464	0.522	0.655	0.473	0.727
16	0.891	0.461	0.518	0.653	0.475	0.728
17	1.716	0.261	0.152	1.447	0.275	0.190
18	1.685	0.250	0.149	1.449	0.254	0.176
19	1.777	0.262	0.148	1.507	0.283	0.188
20	1.782	0.251	0.140	1.531	0.255	0.166

Table 2. Biophysical data from various types of ensembles used for verification of the modeling method (n = 45)

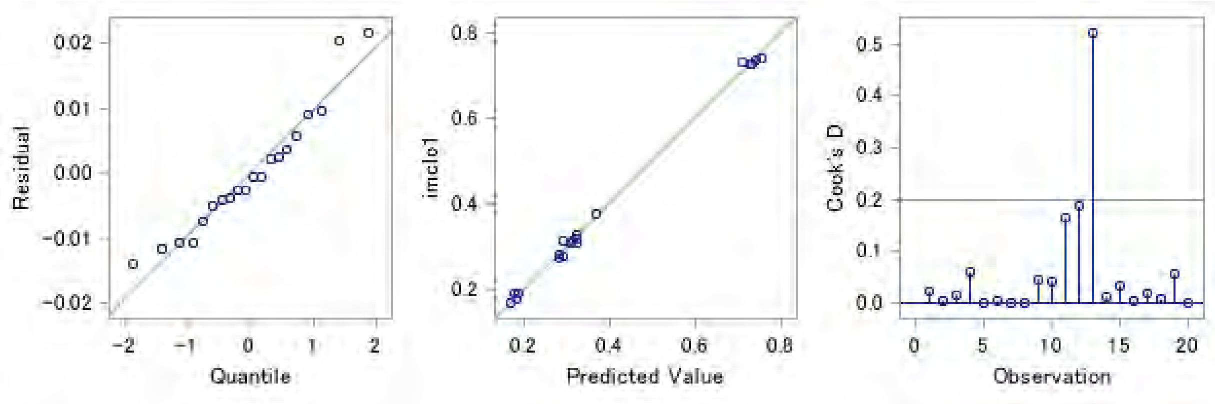
Ensemble	***0.4 m/s*** **clo**	***0.4 m/s*** $\mathbf{i_m}$	***0.4 m/s*** $\mathbf{i_m}$**/clo**	***1 m/s*** **clo**	***1 m/s*** $\mathbf{i_m}$	***1 m/s*** $\mathbf{i_m}$**/clo**
1	1.849	0.266	0.149	1.558	0.286	0.188
2	1.796	0.255	0.142	1.545	0.261	0.168
3	1.405	0.422	0.300	1.118	0.494	0.439
4	1.354	0.451	0.342	1.085	0.499	0.470
5	1.466	0.437	0.306	1.184	0.479	0.413
6	1.323	0.475	0.374	1.052	0.524	0.513
7	1.302	0.468	0.372	1.040	0.517	0.510
8	1.675	0.440	0.269	1.344	0.469	0.356
9	1.373	0.483	0.365	1.086	0.512	0.481
10	1.423	0.537	0.333	1.116	0.496	0.457
11	1.524	0.400	0.286	1.240	0.404	0.364
12	1.648	0.422	0.256	1.338	0.433	0.330
13	1.603	0.433	0.270	1.286	0.453	0.360
14	1.641	0.453	0.276	1.307	0.468	0.365
15	1.614	0.416	0.258	1.298	0.424	0.332
16	1.290	0.421	0.374	1.035	0.457	0.468
17	1.393	0.430	0.339	1.097	0.462	0.440
18	1.651	0.429	0.252	1.351	0.429	0.326
19	1.926	0.411	0.220	1.517	0.442	0.298
20	2.079	0.402	0.195	1.712	0.424	0.253
21	2.530	0.394	0.147	2.203	0.415	0.183
22	2.392	0.360	0.167	1.939	0.394	0.218
23	2.582	0.349	0.135	2.248	0.387	0.172
24	1.832	0.280	0.152	1.504	0.295	0.196
25	1.976	0.310	0.157	1.657	0.339	0.205
26	2.002	0.304	0.152	1.697	0.319	0.188
27	1.894	0.148	0.079	1.577	0.165	0.105
28	2.016	0.301	0.149	1.722	0.320	0.185
29	2.033	0.294	0.145	1.733	0.316	0.182
30	1.740	0.264	0.151	1.436	0.276	0.192
31	2.231	0.284	0.128	1.925	0.297	0.154
32	1.729	0.293	0.172	1.416	0.314	0.223
33	1.864	0.330	0.178	1.577	0.355	0.226
34	1.868	0.320	0.171	1.616	0.339	0.210
35	1.773	0.157	0.088	1.467	0.174	0.119
36	1.934	0.301	0.156	1.609	0.328	0.204
37	1.945	0.301	0.155	1.632	0.324	0.199
38	3.031	0	0	2.3603	0	0
39	3.209	0	0	2.7661	0	0
40	3.039	0	0	2.5021	0	0
41	3.501	0	0	3.0625	0	0
42	1.51	0.373	0.25	1.251	0.380	0.304
43	1.51	0.418	0.28	1.258	0.427	0.340
44	1.90	0.448	0.24	1.533	0.516	0.337
45	1.63	0.373	0.23	1.348	0.398	0.296

RESULTS

Using the model dataset from Table 1, the forward adding stepwise multiple linear regression method generated the following equation predicting i_m/clo at 1 m/s from standard 0.4 m/s measurements with an $R^2 = 0.998$:

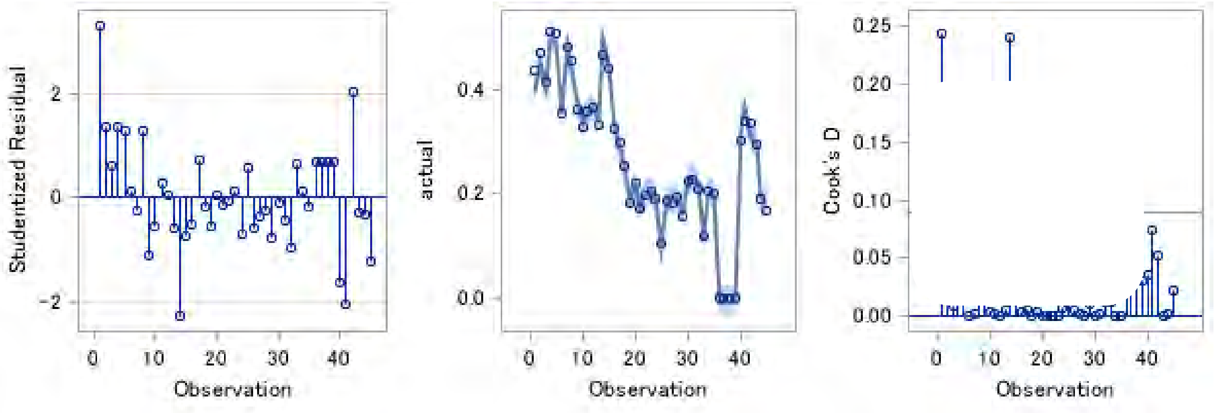
$$\frac{i_m}{clo}(1.48) - 0.04 \qquad [Eq\ 1]$$

Figure 1. Statistical summary of Equation 1 regression model



Equation 1 was applied to each of the ensembles in Table 2, and compared to their measured values for i_m/clo. This model RMSE = 0.013 and MAE = 0.009.

Figure 2. Summary of root mean squared error (RMSE) and mean absolute error (MAE) using Equation 1 on verification dataset



DISCUSSION

The results from this analysis shows that reasonable estimates of clo and i_m can be obtained using only standard ASTM measurements. This work shows that when only standard measures of thermal and evaporative resistance are available, reasonable values of clo and i_m needed for modeling can be estimated using a combination of the method outlined here in Equation 1 and those described in Potter et al. [8]. Specifically, models such as the Heat Strain Decision Aid (HSDA) use biophysical inputs of clo and a clo(^{g}) and i_m/clo and i_m/clo(^{g}) measured at 1 m/s. Collectively the set of equations in Table 3 can be used to estimate these inputs using ASTM standard measurements made a 0.4 m/s wind velocity:

Table 3. Equations used to estimate inputs to the SCENARIO or HSDA model from biophysical measures made at ASTM standard 0.4 m/s wind velocity

Input	Equation
clo 1 m/s	$clo(0.782) - i_m(0.827) + 0.333$
clo(^{g})	$clo(0.079) - i_m(0.516) - 0.182$
i_m/clo 1 m/s	$\frac{i_m}{clo}(1.48) - 0.04$
i_m/clo(^{g})	$i_m(0.466) - clo(0.068) + 0.216$

It is important to note that given the option and availability, measurements at multiple wind velocity are ideal. The multiple measures also reduce the likelihood of missing atypical wind velocity effects possible from unusually porous textile types. However, there are also complexities surrounding current methods of modeling effects of wind permeation of clothing that occur at higher wind velocities. In most climate controlled chambers, testing for the biophysics at three wind velocities can typically only be done with an upper level wind velocity of ~2.5 m/s. However, in more extreme environmental conditions (i.e., wind velocities over 2.5 m/s) and when unusually porous clothing is used, the changes to the clothing may unobservable in chamber testing conditions.

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