U.S. Army
Research Institute of
Environmental Medicine
Natick, Massachusetts

TECHNICAL REPORT NO. T14-7
DATE July 2014
ADA

IMPACT OF ESTIMATING THERMAL MANIKIN DERIVED WIND VELOCITY COEFFICIENTS ON PHYSIOLOGICAL MODELING

United States Army
Medical Research & Materiel Command

DISCLAIMERS

USARIEM TECHNICAL REPORT T14-7

IMPACT OF ESTIMATING THERMAL MANIKIN DERIVED WIND VELOCITY COEFFICIENTS ON PHYSIOLOGICAL MODELING

Adam W. Potter
Julio A Gonzalez
Anthony J. Karis
Timothy P. Rioux
Laurie A. Blanchard
Xiaojiang Xu

Biophysics and Biomedical Modeling Division

July 2014

U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
28-07-2014	Technical Report	2014

4. TITLE AND SUBTITLE

IMPACT OF ESTIMATING THERMAL MANIKIN DERIVED WIND VELOCITY COEFFICIENTS ON PHYSIOLOGICAL MODELING

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Adam W. Potter
Julio A Gonzalez
Anthony J. Karis
Timothy P. Rioux
Laurie A. Blanchard
Xiaojiang Xu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Biophysics and Biomedical Modeling Division
U.S. Army Research Institute of Environmental Medicine
Building 42 - Kansas Street, Natick, MA 01760

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Materiel Command
Fort Detrick, MD 21702

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

It is well understood that thermal strain will occur from working in hot conditions or at moderate to high work rates, and that this impact varies with wind velocity. One method for addressing the wind velocity effect on insulation and evaporative resistance includes conducting standardized thermal manikin testing followed by additional custom tests. This current method tests at the standard one wind velocity (0.4 m/s) as well as at two additional wind speeds, for a total of six tests (i.e., 3 for insulation and 3 for evaporative resistance). This process seeks to create a set of measures to produce the gradient effect of wind, in order to obtain associated coefficients. This report outlines mathematical methods for determining reasonable estimates of wind velocity effect on biophysical measures using only the standardized test methods. This new method will empower using the standard approach, for modeling purposes, while economically adding a simpler method for determining wind velocity effects.

15. SUBJECT TERMS

human endurance; thermoregulation; performance; ergonomics; thermal strain; thermal resistance; evaporative resistance

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Adam W. Potter
					***19b.* TELEPHONE NUMBER** *(Include area code)*
UNCLASS	UNCLASS	UNCLASS	Unclassified	16	508-233-4735

TABLE OF CONTENTS

Section ... Page

List of Figures ... iv

List of Tables ... iv

Acknowledgments ... v

Executive Summary ... 1

Introduction ... 2

Methods ... 3
- Statistical Analysis ... 3
- Verification ... 4
- Biomedical Modeling Validation ... 4

Results ... 4
- Biophysical Assessments ... 4
- Statistical Model Analysis ... 5
- Biomedical Modeling Validation ... 8

Discussion ... 10

Conclusions ... 11

Recommendations ... 11

References ... 12

LIST OF FIGURES

Figure		Page
1	Predictions of clo using 2 point estimation compared to 3 point measured for a) 1 m/s and b) 1.8 m/s	7
2	Predictions of clo using 1 point estimation method compared to 3 point measured for a) 1 m/s and b) 1.8 m/s	7
3	Impact of using estimated and actual aV^g values to model temperate conditions (35°C; 50% RH, 1 m/s) at three work intensities (180, 300, 500W)	8
4	Impact of using estimated and actual aV^g values to model jungle conditions (35°C; 75% RH, 1 m/s) at three work intensities (180, 300, 500W)	9
5	Impact of using estimated and actual aV^g values to model desert conditions (48.89°C; 20% RH, 1 m/s) at three work intensities (180, 300, 500W)	9

LIST OF TABLES

Table		Page
1	Modeled (group I) and verification (group II) ensembles at ASTM 0.4 m/s	4
2	Modeled (group I) and verification (group II) ensembles at 1.0 m/s	5
3	Modeled and verification ensemble wind velocity coefficients	5
4	Pearson Correlation of modeled variables for clo^g	5
5	Pearson Correlation of modeled variables for i_m/clo^g	5
6	Verification data wind velocity coefficients compared to estimated values	6

ACKNOWLEDGMENTS

The authors would like to thank William Tharion, William Santee, Mark Buller, and Larry Berglund for their guidance and discussions related to this work. The authors would also like to thank Reed Hoyt and Alyssa Carter for reviewing and editorial assistance in preparing this technical report.

EXECUTIVE SUMMARY

Measuring the biophysical characteristics of clothing and modeling the associated physiological impacts on the human is of significant interest to modelers, researchers, physiologists, and clothing developers. It is well understood that thermal strain will occur from working in hot conditions or at moderate to high work rates, and that this impact varies with wind velocity.

While there are ASTM standard test methods for comparing differences in biophysical characteristics of clothing ensembles, the methods for determining and modeling the changes that wind velocity has on heat and vapor transport are not well standardized. One method for addressing the wind velocity effect on insulation and evaporative resistance includes conducting standardized thermal manikin testing followed by additional custom tests. This current method tests at the standard one wind velocity (0.4 m/s) as well as at two additional wind speeds, for a total of six tests (i.e., 3 for insulation and 3 for evaporative resistance). This process seeks to create a set of measures to produce the gradient effect of wind, in order to obtain associated coefficients.

This report outlines mathematical methods for determining reasonable estimates of wind velocity effect on biophysical measures using only the standardized test methods. This new method will empower using the standard approach, for modeling purposes, while economically adding a simpler method for determining wind velocity effects.

INTRODUCTION

The effect of wind velocity on the biophysical characteristics of clothing is of significant interest to modelers, researchers, physiologists, and clothing developers. It is known that thermal strain will occur from working in hot conditions or at higher work intensities, and that this impact can be modified by the effects of wind velocity. Currently there are standardized testing methods for comparing different clothing ensembles as well as accepted modeling and simulation methods. The effects of wind velocity are well recognized within this community. Methods of determining this wind effect on the insulation and evaporative potential of clothing and the associated physiological impacts are less well understood and currently require unconventional testing outside of the standard methods.

Thermoregulatory models such as Heat Strain Decision Aid (HSDA) (Givoni & Goldman, 1972; Gonzalez et al, 1997), or SCENARIO (Kraning & Gonzalez, 1997), predict thermo-physiological responses to various environments, clothing, and physical activities. These models specifically address heat transfer from the human, through clothing, to the environment. Critical inputs to these models are the effect that different wind velocity has on thermal insulation and evaporative resistance. For this reason, custom testing methods have been developed to measure the wind velocity effect on varying clothing ensembles.

Using a heated thermal manikin, each ensemble must be tested to ASTM standards for measuring thermal insulation (ASTM F1291-10) at 0.4 m/s (0.89 mph) and then again for evaporative resistance (ASTM F2370-10) at 0.4 m/s. Following these standard tests, additional tests are conducted at two higher wind speeds in order to obtain a wind speed effect coefficient.

The current estimation method for dry thermal insulation (clo) of ensembles includes testing at wind speeds of 0.4 m/s (0.89 mph), 1.0 m/s (2.24 mph), and 2.0 m/s (4.47 mph). For these tests, the thermal manikin 'skin' surface remains dry and heated to 35°C while the environment is held constant at 23°C and 50% RH. Following the dry thermal insulation testing, the evaporative resistance (i_m) is calculated, under at the same three wind speeds (i.e., 0.4, 1.0, and 2.0 m/s). For these tests, the thermal manikin 'skin' surface is 100% saturated and heated to 35°C and the environmental conditions are held constant at 35°C and 40% RH. Thus, at steady state all heat is loss is via evaporation. Each of these three sets of data a power trend line is developed with an associated wind effect coefficient (^{g}). This equation is gained by:

$$y = a * v^g \quad \text{(Eq 1)}$$

or in logical linear form as:

$$\ln(y) = \ln(a) + g * ln(v) \quad \text{(Eq 2)}$$

where *y* = the specific line (*ln*); *a* = the initial point or constant; *v* = rate of exponential growth; and *g* = growth coefficient.

With respect to the wind effect, we would replace *a* with the points of measurement (thermal insulation or evaporative resistance), *v* with the wind speed, and *g* with the wind effect coefficient. Determining the constant value of *a* becomes part of the basis for estimating wind effects for different velocities.

In theory, convective heat loss can be expressed as a function of wind speed. For clothing insulation we can derive equations based on data collected at one wind speed. This research uses scientific methods for determining reasonable estimates of wind velocity effect on biophysical measures using only the standardized test methods; a reduction from six tests down to only two. Having a method that uses the standard approach will allow for economical testing and conserving of resources, as well as the ability to test significantly more items of interest.

METHODS

The biophysical properties (thermal resistance and evaporative resistance) were assessed on 44 clothing ensembles with varied characteristics. The clothing ranged from physical training (PT) uniform (shorts, t-shirt, socks, and running sneakers), standard Army uniform (underwear, t-shirt, pants, long-sleeved shirt, socks, and combat boots), Army uniform with helmet and full body armor, and chemical protective ensembles (gas mask, fully encapsulating chemical protective suit, gloves, and boots).

Each ensemble was tested to American Society of Testing and Materials International (ASTM) standards for thermal insulation (ASTM F1291-10) and evaporative resistance (ASTM F2370-10) followed by repeated tests at additional wind speeds (standard 0.4 m/s, 1 m/s, and 2 m/s). From these three measures a power trend line was calculated to obtain the associated wind effect coefficient (^{g}) (Eq 1-2). The wind speed coefficients obtained using these methods were used as the standard for comparison against the estimation method developed.

Statistical Analysis

Statistical analyses were performed using SPSS 21.0 Statistical Software (SPSS Inc., an IBM Company, Chicago, IL). Descriptive statistics are presented as means ± standard deviations (SD). A forward adding stepwise multiple linear regression modeling method was used to develop equations from the data to predict wind velocity coefficients for both the thermal resistance (cloV^g) and the vapor permeability ratio (i_m/cloV^g)) using half of the dataset (N=22) (group I).

Verification

Verification analysis was conducted using half of the dataset (N=22) (group II) of ensembles tested at the ASTM standard and at the same additional wind speeds. Actual and predicted values of cloV^g and i_m/cloV^g were compared and outlined to show percent deviation.

Biomedical Modeling Validation

Validation analysis was conducted using the worst-fit ensemble data (cloV^g) error = 0.04 (i_m/cloV^g) error = 0.12) to the developed equations, modeled using equations from the heat strain modeling methods outlined by Gonzalez et al (1997). From this method a comparison was made to show the overall outcome differences modeled at 1 m/s using the actual and predicted wind speed coefficients up to a predicted critical internal core body temperature (T_c) of 39°C (102.2°F).

Simulations for the model assumed a normally hydrated male, weighing 70 kg, 172 cm tall, a surface area of 1.8 m^2, and heat acclimated 12 days. During each simulation, the individual was modeled at three work intensities typical of military tasks: light (180 W), moderate (300 W), and high (500 W). Modeling was conducted to simulate three night time environmental conditions: Desert (48.89°C; 20% RH); Jungle (35°C; 75% RH), and Temperate (35°C; 50% RH), with wind speeds of 1 m/s (Potter et al, 2013).

RESULTS

Biophysical assessments

Biophysical properties of 44 ensembles were assessed, with 22 ensembles used for modeling (group I) and 22 ensembles used for verification (group II) (Tables 1, 2). For this assessment, only the values collected at the ASTM 0.4 m/s and 1.0 m/s are reported, as the additional data at 2 m/s wind speed follows this curvilinear line.

Table 1. Modeled (group I) and verification (group II) ensembles at ASTM 0.4 m/s

Variable	***Group I***		***Group II***	
	Mean ± SD	Range	Mean ± SD	Range
n	22		22	
clo (thermal resistance)	1.469 ± 0.332	0.877 to 1.849	1.679 ± 0.390	1.290 to 2.582
i_m (vapor permeability)	0.366 ± 0.078	0.250 to 0.473	0.431 ± 0.041	0.349 to 0.537
i_m/clo (evaporative potential)	0.277 ± 0.142	0.140 to 0.536	0.278 ± 0.072	0.135 to 0.374

Table 2. Modeled (group I) and verification (group II) ensembles at 1.0 m/s

Variable	***Group I***		***Group II***	
	Mean ± SD	Range	Mean ± SD	Range
n	22		22	
clo (thermal resistance)	1.056 ± 0.285	0.646 to 1.290	1.375 ± 0.363	1.035 to 2.248
i_m (vapor permeability)	0.411 ± 0.048	0.350 to 0.478	0.453 ± 0.042	0.387 to 0.524
i_m/clo (evaporative potential)	0.441 ± 0.205	0.270 to 0.742	0.363 ± 0.104	0.172 to 0.513

The wind velocity coefficients (^{g}) being a function of the three wind speed tests remain constant across each measure (Table 3).

Table 3. Modeled and verification ensemble wind velocity coefficients

Variable	***Group I***		***Group II***	
	Mean ± SD	Range	Mean ± SD	Range
n	22		22	
clo$\boldsymbol{V^g}$	-0.255 ± 0.066	-0.370 to -0.164	-0.230 ± 0.032	-0.265 to -0.151
i_m/clo$\boldsymbol{V^g}$	0.287 ± 0.064	0.178 to 0.397	0.293 ± 0.052	0.185 to 0.438

Statistical Model Analysis

Estimated wind velocity coefficients were derived using only the standard testing measures (0.4 m/s) seen in Table 1. Variable correlation was conducted prior to modeling using Pearson Correlation (Tables 4, 5).

Table 4. Pearson Correlation of modeled variables for clo^g

Variable	***clo$\boldsymbol{V^g}$***	***clo***	***i_m***
clo$\boldsymbol{V^g}$	1.000	0.926	-0.955
clo	0.926	1.000	-0.865
i_m	-0.955	-0.865	1.000

Table 5. Pearson Correlation of modeled variables for i_m/clo^g

Variable	***i_m/clo$\boldsymbol{V^g}$***	***clo***	***i_m***
i_m/clo$\boldsymbol{V^g}$	1.000	-0.838	0.867
clo	-0.838	1.000	-0.865
i_m	0.867	-0.865	1.000

The first step in developing the predictive method using only one wind velocity is estimation of the constant value (*a*). This constant value would be specific for both the estimation of clo as well as the i_m/clo estimation.

For estimating *a* from the standard one wind velocity testing procedure, linear regression modeling was used to obtain the two models: Model 1a (M1a) uses only a measure of clo at 0.4 m/s, categorized as: R = 0.994; R^2 = 0.988, an adjusted R^2 = 0.987; SE = 0.03593, shown as:

$$a = clo(0.948) - 0.215 \qquad \text{(M1a)}$$

Model 1b (M1b) uses measures of both i_m and clo at 0.4 m/s, categorized as: R = 0.999; R^2 = 0.998, an adjusted R^2 = 0.998; SE = 0.01462, shown as:

$$a = clo(0.782) - i_m(0.827) + 0.333 \qquad \text{(M1b)}$$

One model (M2) can be used for estimating the constant (*a*) for the i_m/clo estimation. This model uses only a value of clo measured at 0.4 m/s, categorized as: R = 0.993; R^2 = 0.986, an adjusted R^2 = 0.985; SE = 0.02590, shown as:

$$a = 1.291 - clo(0.627) \qquad \text{(M2)}$$

The next step in developing the model (M3) for predicting this wind effect is to determine the exponent power effect from the wind (^{g}). Using multiple linear regression with only these two data points for estimating the constant (^{g}) for clo was categorized as: R = 0.975; R^2 = 0.952, an adjusted R^2 = 0.946; SE = 0.01518, shown below:

$$g = clo(0.079) - i_m(0.516) - 0.182 \qquad \text{(M3)}$$

This same multiple linear regression method was used to develop the model (M4) using only these two data points for estimating the wind effect (^{g}) for i_m/clo was categorized as: R = 0.885; R^2 = 0.782, an adjusted R^2 = 0.760; SE = 0.03148, shown below:

$$g = i_m(0.466) - clo(0.068) + 0.216 \qquad \text{(M4)}$$

The modeled equations were applied to the verification data and the measured values coefficients compared closely (Table 6).

Table 6. Verification data wind velocity coefficients compared to estimated values

Variable	***Actual***	***Estimated***	***Absolute error***	***Error range***
n	22			
clo$\boldsymbol{V^g}$	-0.230 ± 0.032	-0.272 ± 0.048	-0.04	-0.10 to 0.05
i_m/clo$\boldsymbol{V^g}$	0.293 ± 0.052	0.303 ± 0.042	-0.01	-0.12 to 0.12

Using the initial equation of $y = a * v^g$, the predicted model equations can be used to substitute values to determine clo and i_m/clo. Measuring at two points instead of three can be done simply, as the nature of the power regression allows for a minimum of two points for defining the line. Measuring at only the one wind speed for clo we can apply model M1a or M1b in place of the constant (*a*), the desired wind speed (*v*), and use model M3 for the coefficient value (^{g}). This same method can be applied to the i_m/clo using M2 as constant (*a*) and M4 for the coefficient value (^{g}).

Figure 1. Predictions of clo using 2 point estimation compared to 3 point measured for a) 1 m/s and b) 1.8 m/s

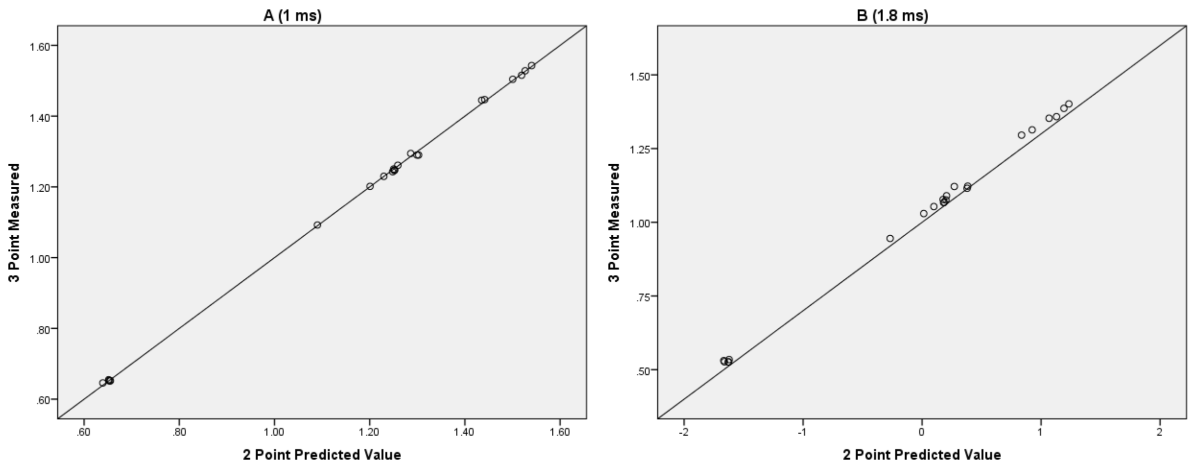
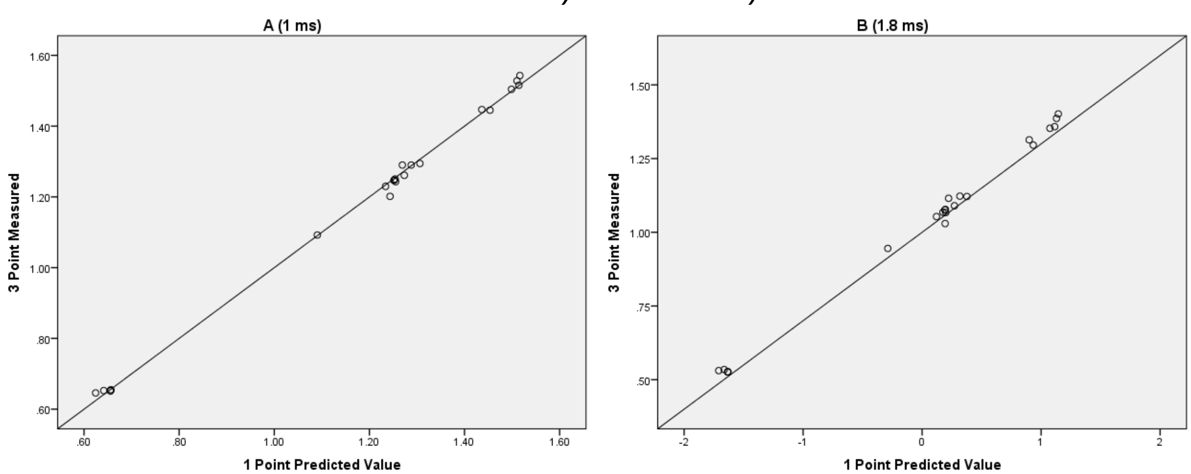


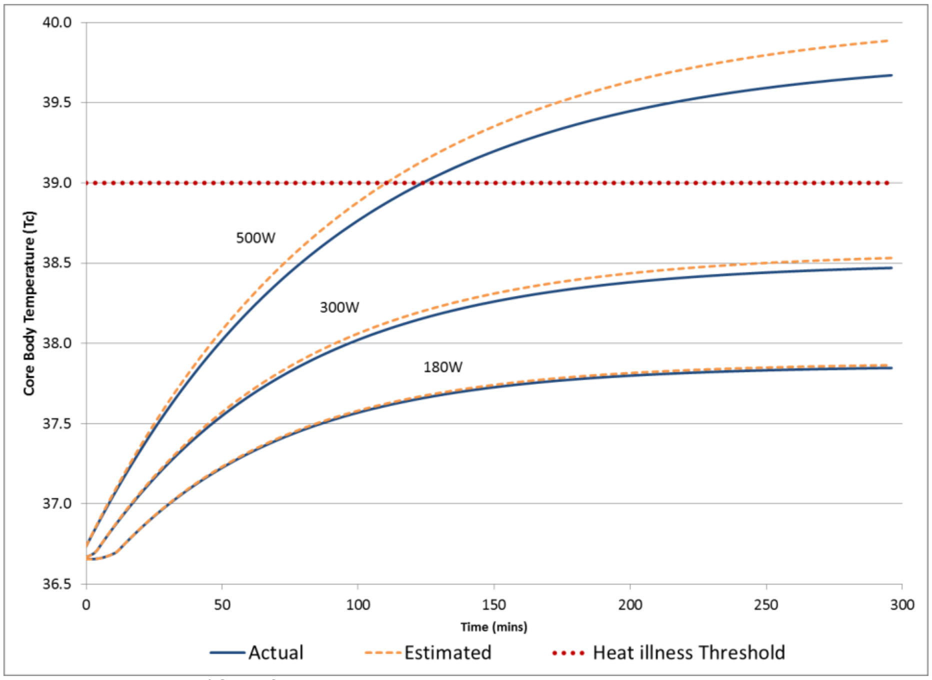
Figure 2. Predictions of clo using 1 point estimation method compared to 3 point measured for a) 1 m/s and b) 1.8 m/s



Biomedical Modeling Validation

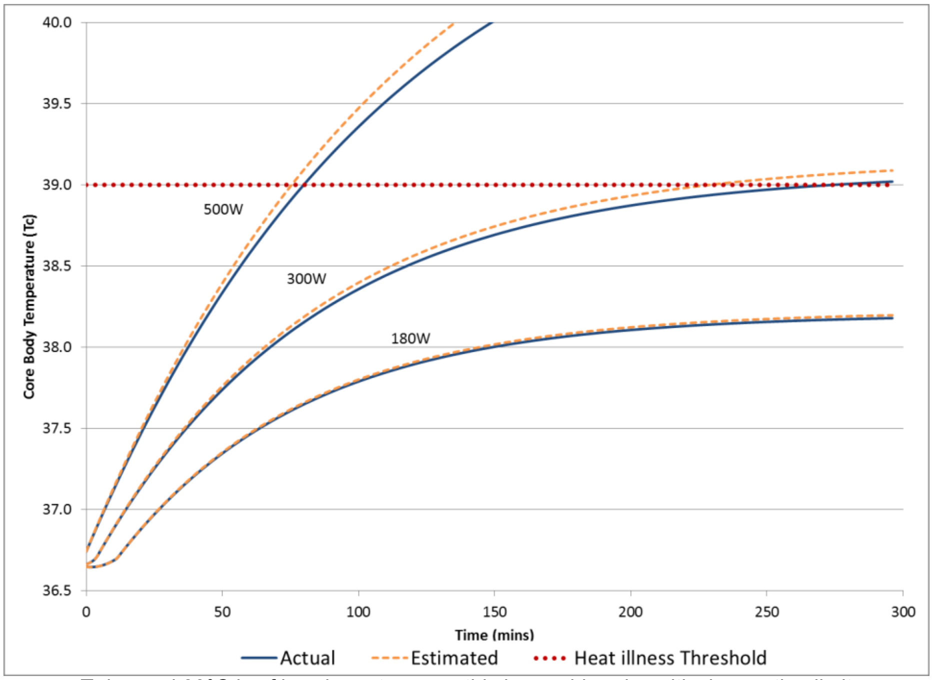
Modeling of the worst-fit ensemble was conducted in three environmental conditions and at three different work intensities. The actual cloV^g and i_m/cloV^g values were compared to the estimated values (Figures 3 – 5).

Figure 3. Impact of using estimated and actual aV^g values for modeling temperate conditions (35°C; 50% RH, 1 m/s) at three work intensities (180, 300, 500W)



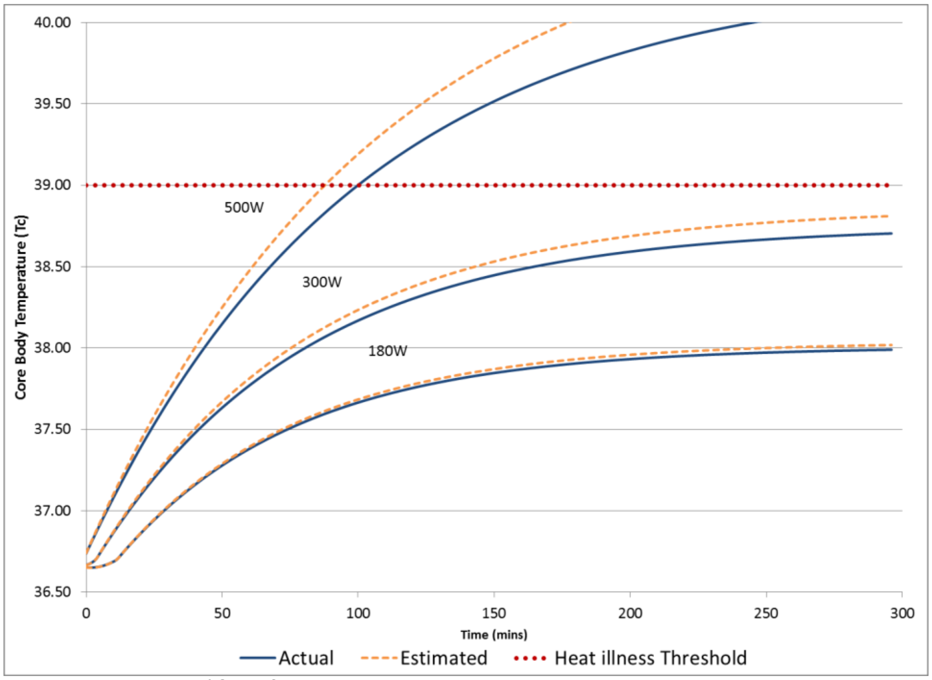
T_c beyond 39°C is of less importance as this is considered a critical operating limit

Figure 4. Impact of using estimated and actual aV^g values to model jungle conditions (35°C; 75% RH, 1 m/s) at three work intensities (180, 300, 500W)



T_c beyond 39°C is of less importance as this is considered a critical operating limit

Figure 5. Impact of using estimated and actual aV^g values to model desert conditions (48.89°C; 20% RH, 1 m/s) at three work intensities (180, 300, 500W)



T_c beyond 39°C is of less importance as this is considered a critical operating limit

Using the worst-fitting data with this estimation method we can see that there is some separation in the predictions when applied to a physiological model. The areas of most concern are at the points where predictions reach the critical core temperature of 39°C. In temperate conditions working at light (180W) or moderate (300W) intensities there was very little difference; while working at high (500W) intensity the estimation method is more conservative in its prediction by 12 minutes. Working in desert conditions at light (180W) or moderate (300W) intensities little differences are observable; while working at high (500W) intensity the estimation under predicts by 11 minutes compared with using data from three wind speeds. In jungle conditions each of the work intensities stayed relatively close with only a 3 minute under prediction at 500W. It is important to note that the largest separation numerically to reach the critical 39°C point was observed in jungle conditions working at moderate (300W) intensity. However, this can be explained as both lines begin to flatten and run along the critical point, causing a larger separation at that point.

DISCUSSION

From a numerical standpoint the results show reasonable estimates can be obtained using this method along with the standardized ASTM single wind speed tests. Furthermore, from a comparison standpoint if all ensembles use this same estimation method there should be consistency in their observed rankings (i.e., constraints should remain consistent in each comparison).

While there is a tight closeness of fit between most cases of estimation and actual measures, we can see from the worst-fit data that there would be observable differences. Therefore, comparing ensembles using the different methods at this point is not recommended.

This data suggests a number of factors create changes in the insulation and evaporative resistance of the ensembles based on wind velocity. Some areas that deserve follow-on research include exposed surface area, clothing layers, and the difference in manikins or technologies. Having more exposed surface area likely causes more impact on the evaporative and thermal resistance of the ensemble, as there is a direct impact of convective heat exchange and evaporation caused by the wind. Therefore, follow-on work should include capturing of and possibly reporting of the exposed surface areas for each ensemble. Along these same lines, the layering of full ensembles should be seen as an indicator of changes in insulation and evaporative resistance. Specifically the addition of layers and the associated change in the internal boundary (air) insulation. It can be reasonably assumed that with more layers the wind velocity will create less internal air layer changes compared to ensembles with fewer layers. Therefore, the number of layers should be included as follow-on inputs to this estimation process. Different manikin technologies and methods should be assessed for differences in this approach. While in the current work there are multiple manikins technologies used as well as different methods (i.e., copper manikins versus carbon fiber; and sweating manikins versus non-sweating).

The worst-fit data was used to show the likely worst case scenario of prediction when used as inputs to accepted heat strain modeling methods. However, this data was significantly further out of range compared to other ensemble data (Figure 4, first point) and could potentially be considered an outlier. While this data was not typical compared to the rest of the dataset and can be explained, as it was the oldest data collected on an outdated manikin system, it was not excluded as to find the limitations of this method. It could be speculated that there could be errors in the data or lower resolution in the method of collection; however, as a physics-based method there should be little differences. Therefore, this further exposes the question of manikin technologies and method differences. That said, using solely standardized test methods may allow for broader modeling and analysis capabilities.

CONCLUSIONS

This work shows that wind velocity coefficients can be reasonably and scientifically estimated using standard testing methods. While others have attempted to show methods for determining these wind effects (Holmér et al., 1999; Parsons et al., 1999), there has not been complex physiological modeling associated with these methods. This approach has used both an estimation method of the biophysically gained data as well as the physiological modeling associated with these estimations.

RECOMMENDATIONS

This analysis suggests that reasonable estimations can be obtained using only the standard ASTM one wind velocity testing process. Therefore, it is recommended that for expedient ensemble comparisons, or for analyses using data obtained from outside sources this method should be used over the more time consuming three wind speed testing. This saving of time and resources can become significant and will allow for larger collections of data and faster turn-around time for customer-driven analyses.

Given more wind-centric or more complex modeling (e.g., mixed environmental scenarios, etc.) the higher resolution, three wind speed testing method should be used. Uniforms that are expected to be or remain as issued items should be required to have this higher level testing conducted, to allow for complex modeling and simulation as needed.

REFERENCES

1. American Society of Testing and Materials International (ASTM): Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin (ASTM F2370-10). [Standard] Philadelphia, Pa.: ASTM, 2010.

2. American Society of Testing and Materials International (ASTM): Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin (ASTM F1291-10). [Standard] Philadelphia, Pa.: ASTM, 2010.

3. Givoni, B. and Goldman, R. F. Predicting rectal temperature responses to work, environment, and clothing. *Journal of Applied Physiology, 32*: 812-822, 1972.

4. Gonzalez, R. R., McLellan, T. M., Withey, W. R., Chang, S. K., and Pandolf, K. B. Heat strain models applicable for protective clothing systems: comparison of core temperature response. Journal of Applied Physiology, 83(3), 1017-1032, 1997.

5. Holmér, I., Nilsson, H., Havenith, G., and Parsons, K. Clothing convective heat exchange—proposal for improved prediction in standards and models. *Annals of Occupational Hygiene, 43(5)*, 329-337, 1999.

6. Kraning II, K. K. and Gonzalez, R. R. A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration. *Journal of Thermal Biology, 22(4)*, 331-342, 1997.

7. Parsons, K. C., Havenith, G., Holmer, I., Nilsson, H., and Malchaire, J. The effects of wind and human movement on the heat and vapour transfer properties of clothing. *Annals of Occupational Hygiene, 43(5)*, 347-352, 1999.

8. Potter, A. W., Karis, A. J., and Gonzalez, J. A. Biophysical Characterization and Predicted Human Thermal Responses to US Army Body Armor Protection Levels (BAPL). U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T13-5, 2013.