Defense Health Agency

Models and Decision Aids for Prevention of Thermal Injuries in Extreme Environments

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24 September 2020

0745 – 0845 (ET)

Presenter(s)

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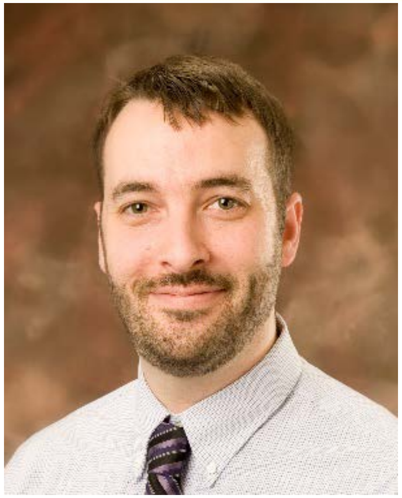

- Dr. Potter is a Research Physiologist and Deputy Chief of the Biophysics and Biomedical Modeling Division (BBMD), at the U.S. Army Research Institute of Environmental Medicine (USARIEM). Prior to working at USARIEM, he spent a number of years in clinical research (drug and device trials). He is U.S. Marine Corps veteran.

Education

- Doctor of Philosophy (PhD) in Biomedical Informatics (Rutgers University)
- Master of Science (MS) in Sport and Health Sciences (American Military University)
- Master of Business Administration (MBA) (American Military University)
- Bachelor of Arts (BA) in Psychology (Cambridge College)

David P. Looney, PhD, CSCS

- Dr. Looney is a Research Physiologist in the Biophysics and Biomedical Modeling Division (BBMD), at the US Army Research Institute of Environmental Medicine (USARIEM). His research focus includes modeling metabolic costs and fatigue during complex military activities.

Education

- Doctor of Philosophy (PhD) in Exercise Science (University of Connecticut)
- Master of Science (MS) in Exercise Science (University of Connecticut)
- Bachelor of Science (BS) in Nutritional Sciences: Dietetics (University of New Hampshire)

Disclosures

Defense Health Agency

- Dr. Adam Potter and Dr. David Looney have no relevant financial or non-financial relationships to disclose relating to the content of this activity.
- The views expressed in this presentation are those of the authors and do not necessarily reflect the official policy or position of the Department of Defense, nor the U.S. Government.
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Learning Objectives

At the conclusion of this activity, participants will be able to:

1. Summarize key elements that affect thermal stress.

2. Identify potential use cases of decision aids.

3. Recognize different types of modeling methods.

U.S. Army Research Institute of Environmental Medicine (USARIEM)

Mission: Protect, sustain, and optimize the health and performance of Service Members through basic and applied research in environmental physiology and occupational medicine.

- Co-located with US Army Natick Soldier Systems Center (SSC)
- A subordinate lab of the US Army's Medical Research and Development Command (USMRDC)
- "World-Class" laboratory for environmental medicine, physiology, performance & nutrition research
- Integrated cellular, tissue, animal & human research programs

[USARIEM, 2020]

USARIEM Facilities

- Center for Military Biomechanics Research
- Doriot Climatic Facility
- High Altitude Laboratory (Pikes Peak CO)
- Hypobaric chambers & hypoxia rooms
- Manikins for heat transfer biophysics
- Thermal Chambers
- Water Immersion Laboratory
- Bone Health Laboratory
- Human Performance Laboratories
- Warfighter Cognitive Performance Lab

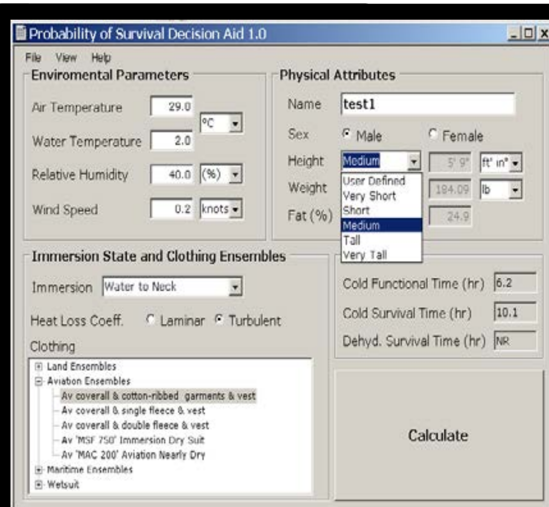
[USARIEM, 2020]

USARIEM Research

Biophysics and Biomedical Modeling Division (BBMD)

DHA
Defense Health Agency

Manikin / physical test measures + Biomedical Mathematical Modeling + Real-Time Health State Monitoring



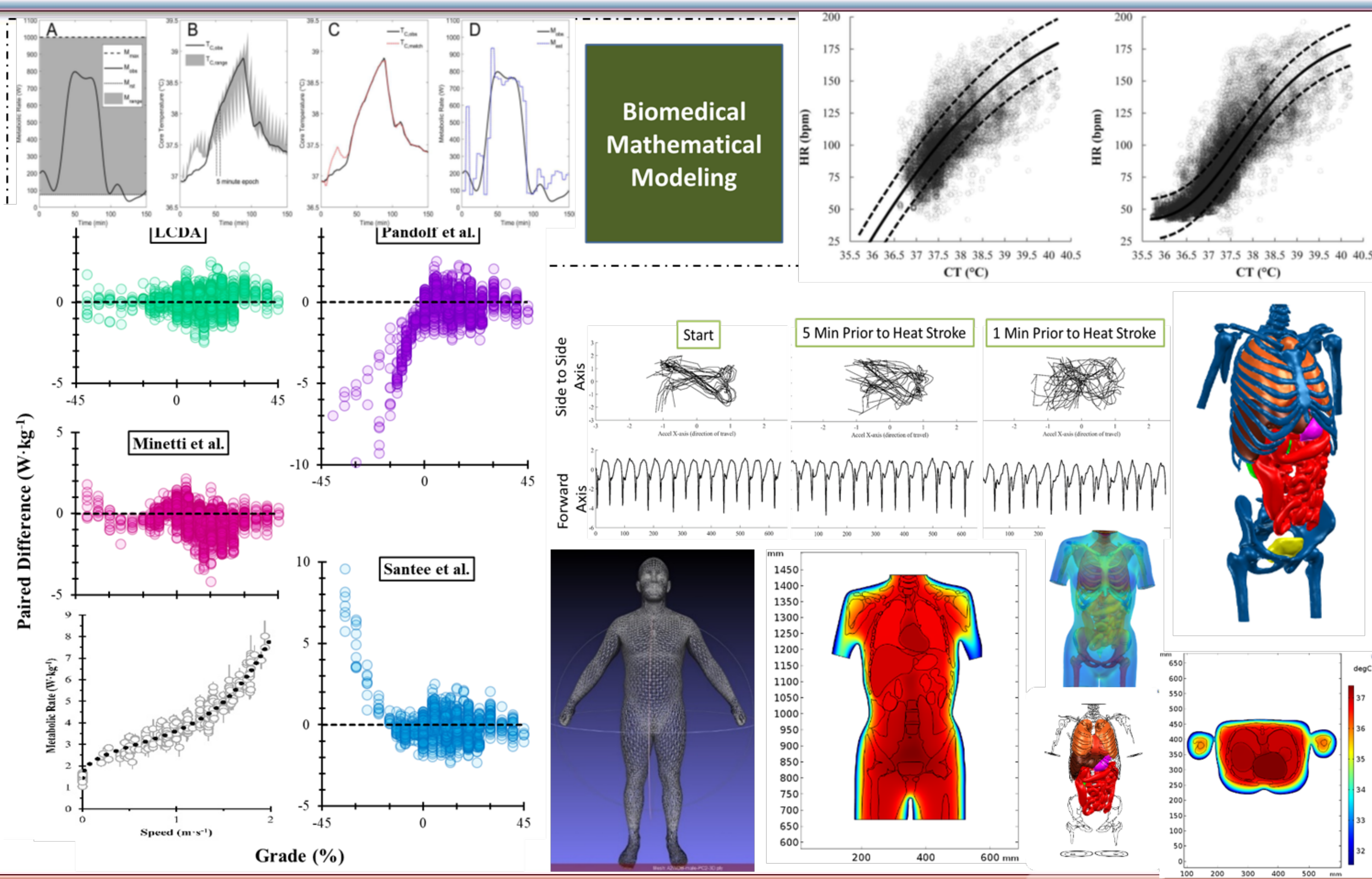
[USARIEM, 2020]

Manikin Testing

Defense Health Agency

[USARIEM, 2020]

Biomedical and Mathematical Modeling

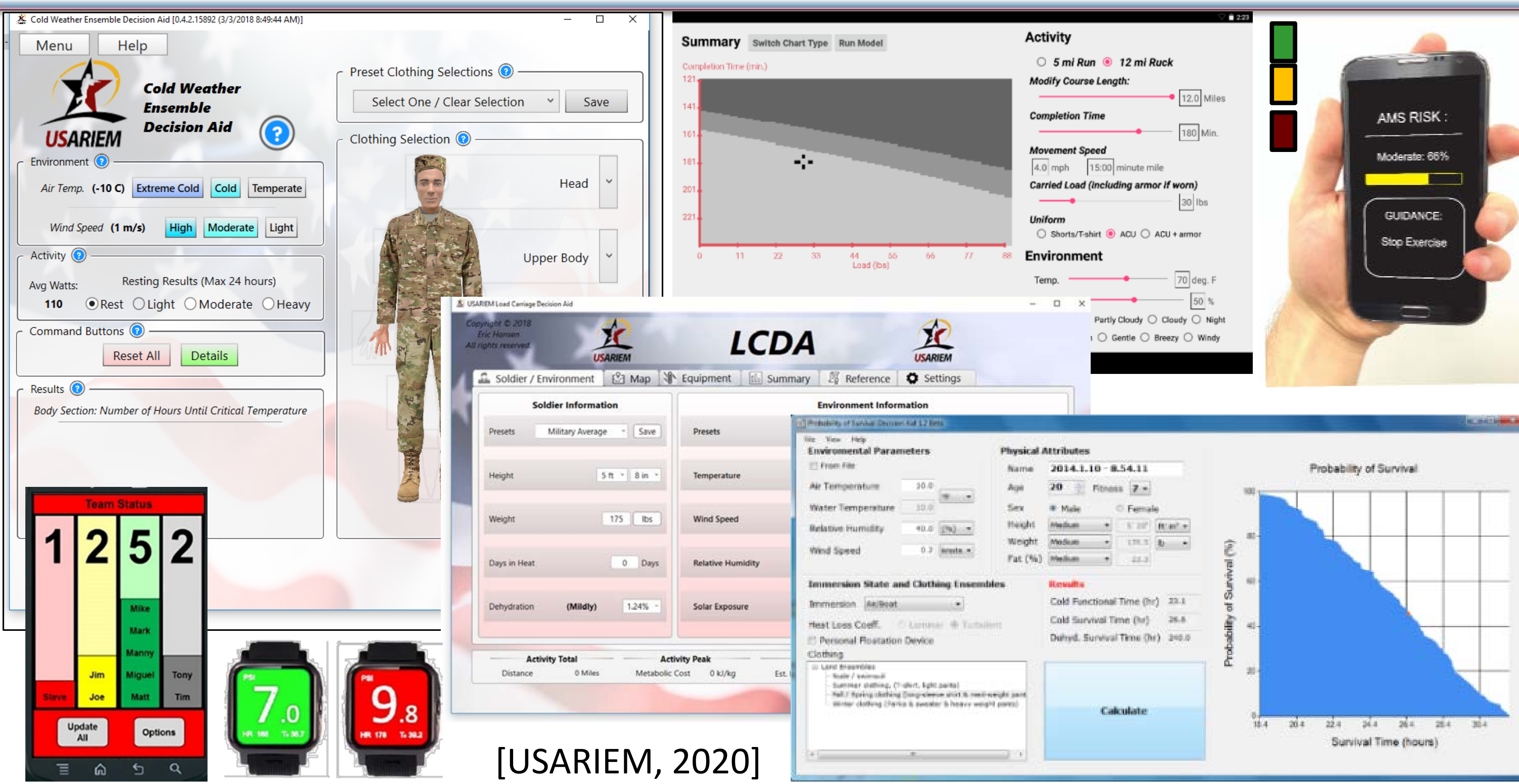


[USARIEM, 2020]

Real-Time Health Status Monitoring

[USARIEM, 2020]

Goal: Practical Solutions



[USARIEM, 2020]

Clothing Biophysical Testing Process

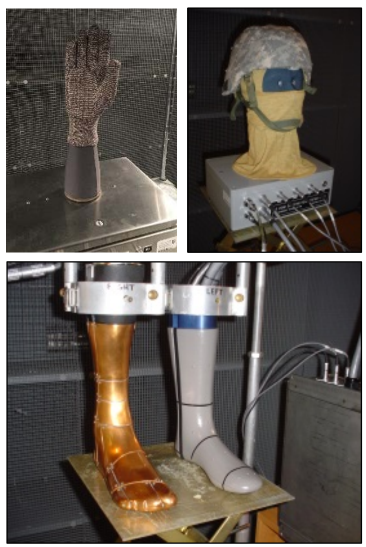
■ Ideal testing process

Swatch Level
- » Sweating Guarded Hotplate (SGHP)
- » Material evaluations for prototype clothing

Individual Component
- » Thermal Hand, Foot, and Head Systems
- » More detailed data for extremities

Full Ensemble
- » Four 20-zone Newton model manikins

Physiological Models
- » Biophysical data – a main input parameter



[Potter et al., 2020b]

Quantifying Relationships

In order to model and predict heat rise or fall in humans, it is important to understand the interrelated elements involved in heat exchange. These individual relationships can be described mathematically.

Broadly, we can characterize heat storage (S) by calculating the sum of heat produced, heat gained, and heat lost. For humans, we simplify this into the heat balance equation:

$$S = M \pm W \pm R \pm C \pm K - E \qquad [\mathrm{W} \cdot \mathrm{m}^{-2}]$$

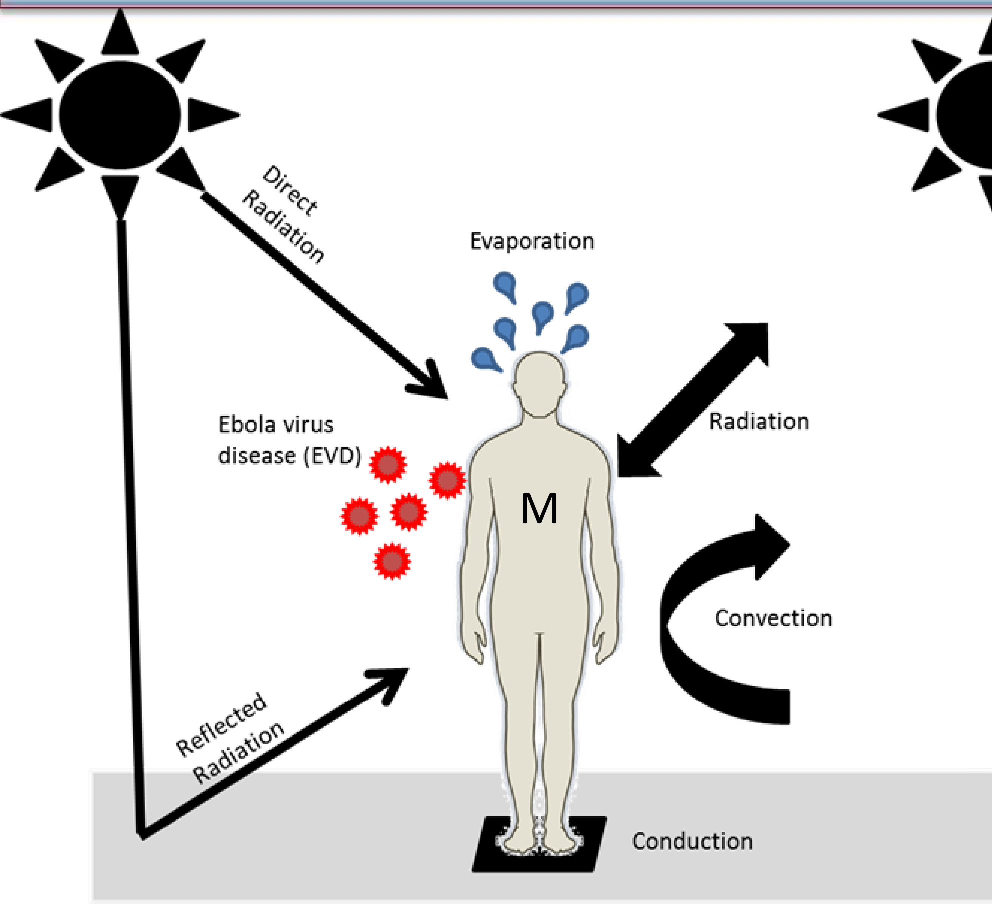
where M is metabolic heat production, W is work rate, R is radiation, C is convection, K is conduction, and E is evaporation.

*The relationship and impact of these elements become more complicated as they are changed (e.g., protective clothing impacts the exchange of heat)

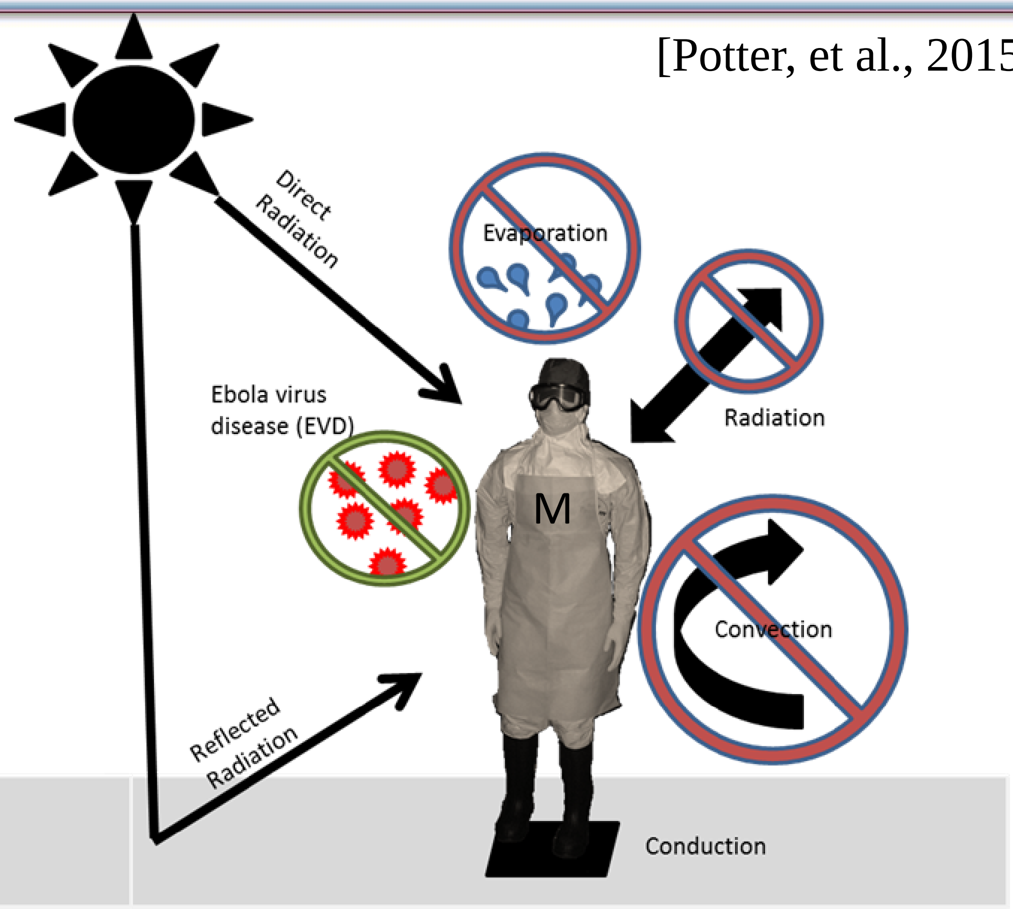
Quantifying Relationships

Human + Clothing + Environment

[Potter, et al., 2015]



Typical clothing



Personal Protective Clothing

Quantifying Relationships

Historically, models have been developed using linear algebra to describe two dimensional relationships (typically the empirical approach); while differential equations have been developed to characterize the three dimensional relationships (typically the rational approach).

$$\rho c \cdot \frac{\partial T}{\partial t} = q_m + \lambda \cdot \nabla^2 T + \omega_{bl} \cdot \rho_{bl} c_{bl} \cdot (T_{bl} - T)$$

$$[W \cdot m^{-3}]$$

[core to skin]

$$-\lambda \cdot \frac{\partial T}{\partial n} = R + C + K + E$$

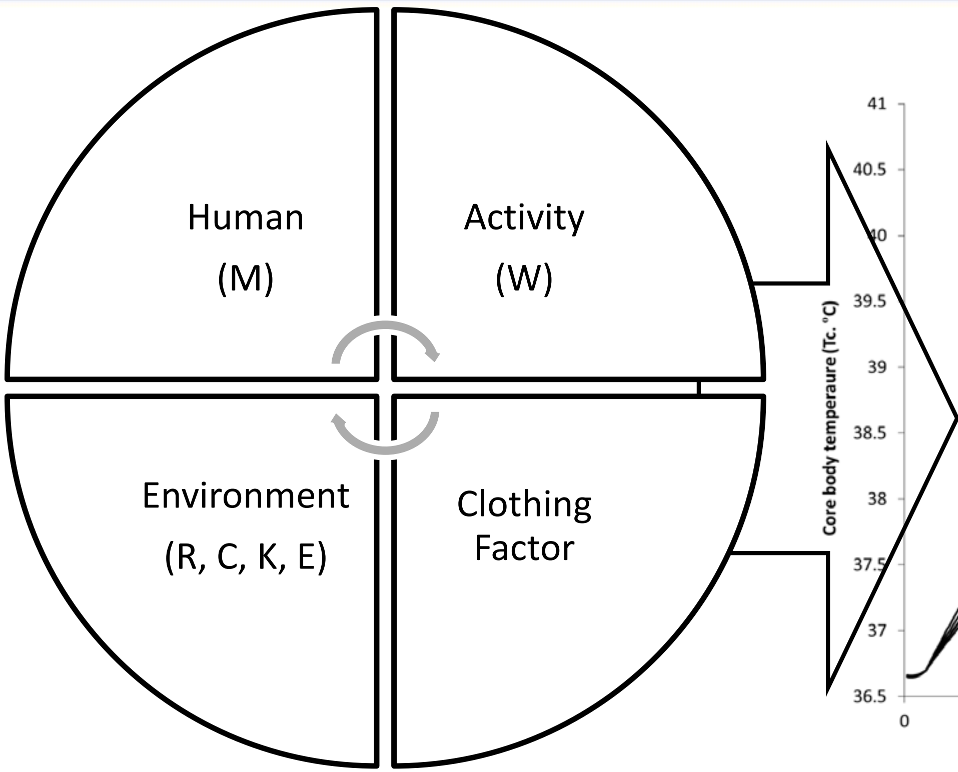
$$[W \cdot m^{-2}]$$

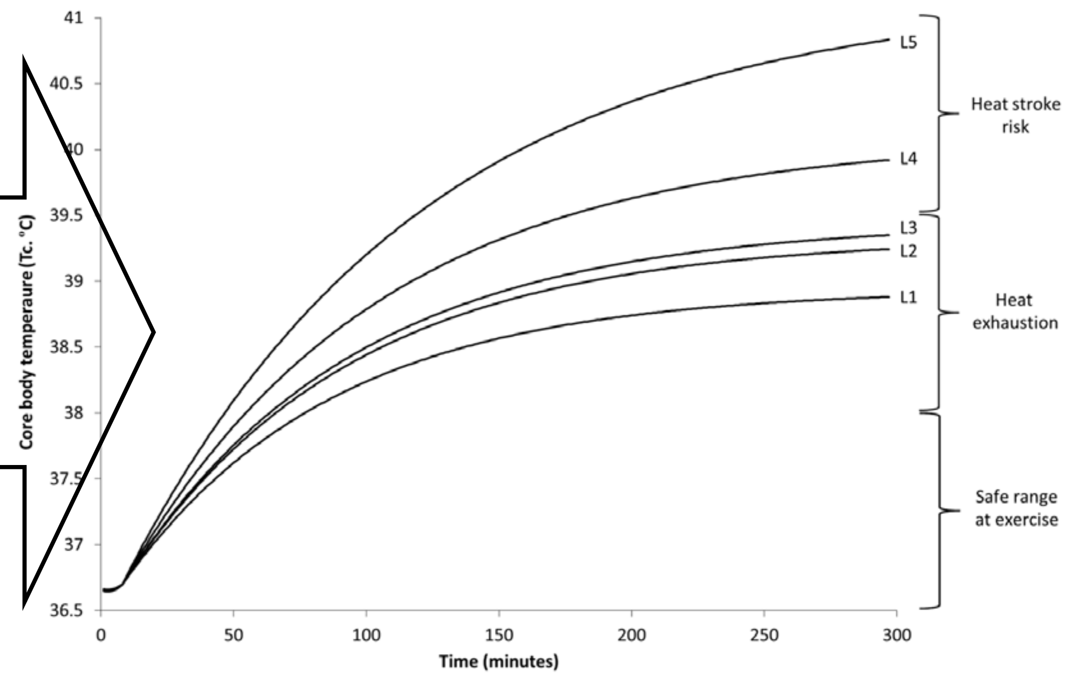
[skin to environment]

where ρ is tissue mass (kg m^{-3}), c is specific heat of the tissue (kJ kg^{-1}°C^{-1}), T is tissue temperature (°C), t is time (sec), q_m is metabolic heat production rate (W m^{-3}), λ is tissue heat conductivity (W m^{-1} °C^{-1}), ∇^2 is a Laplace transform for heat conduction based on the tissue temperature gradient, ω_{bl} is blood flow rate ($m^3 s^{-1} m^{-3}$ tissue), ρ_{bl} is blood flow mass (kg m^{-3}), c_{bl} is blood specific heat (kJ kg^{-1}°C^{-1}), and T_{bl} is blood temperature (°C), n is the tissue coordinate normal to the skin surface

Heat Exchange & Elapsed Time

[Potter, et al., 2015]





Using the backdrop of the heat balance we can model out how much heat is lost, gained, and ultimate stored. This summed storage (positive or negative) can be translated into a rise or fall in core body temperature over time

Metabolic Heat Production

$$S = M \pm W \pm R \pm C \pm K - E \qquad [\mathrm{W \cdot m^{-2}}]$$

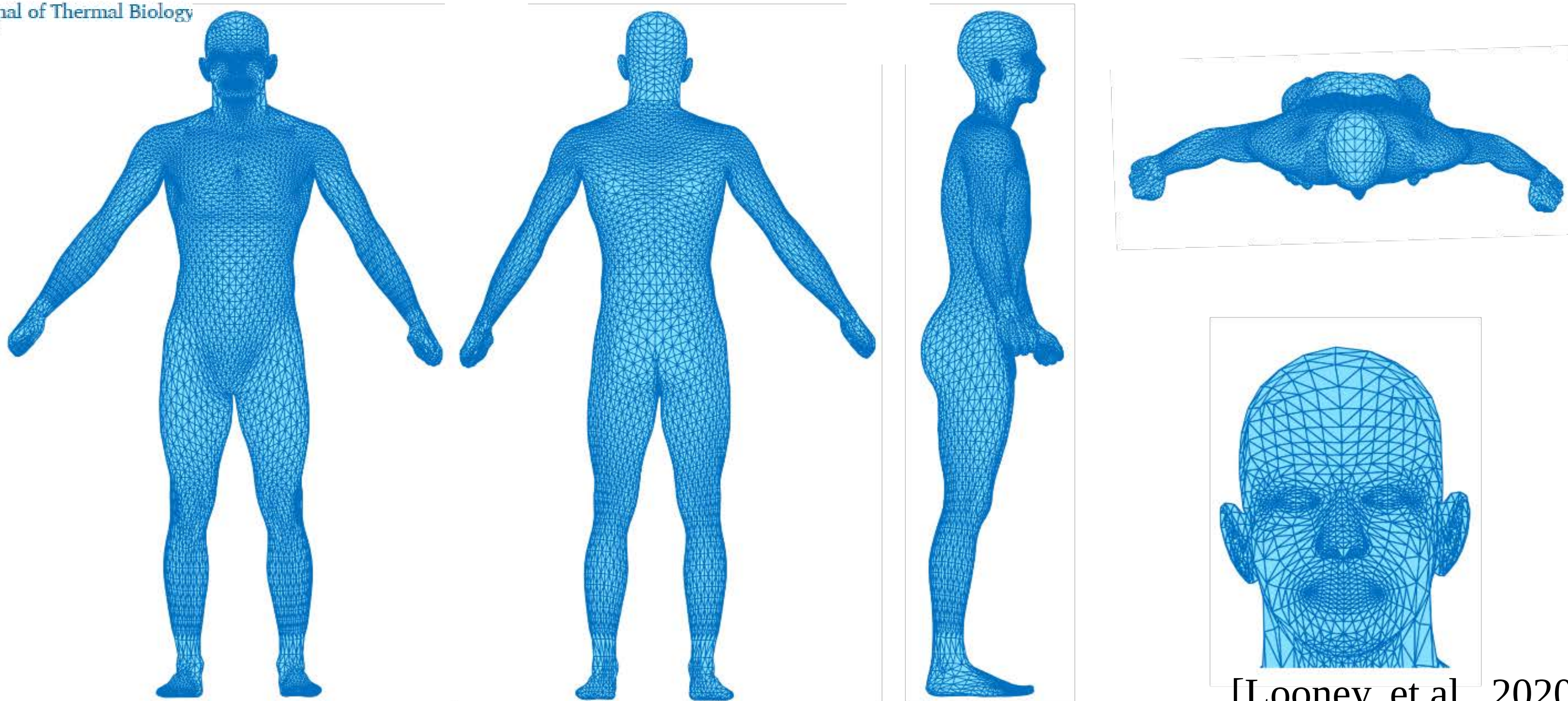
Metabolic Heat Production

Body Surface Area

Formulae for calculating body surface area in modern U.S. Army Soldiers

David P. Looney[a], Diana P. Sanford[a,b], Peng Li[c], William R. Santee[a,b], Elizabeth M. Doughty[a,b], Adam W Potter[a,*]

Journal of Thermal Biology



[Looney, et al., 2020]

Metabolic Heat Production

Movement Speed

Metabolic Costs of Standing and Walking in Healthy Military-Age Adults: A Meta-regression

DAVID P. LOONEY[1], ADAM W. POTTER[1], J. LUKE PRYOR[2], PATRICIA E. BREMNER[3], CHRISTOPHER R. CHALMERS[1,4], HOLLY L. MCCLUNG[1], ALEXANDER P. WELLES[1], and WILLIAM R. SANTEE[1,4]

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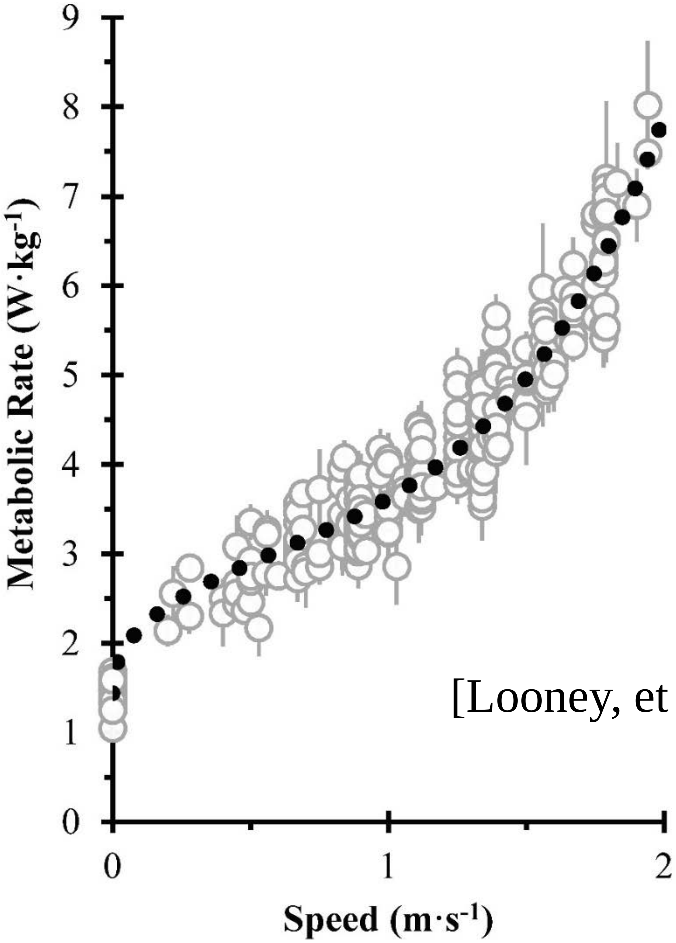

"Medically Ready Force…Ready Medical Force"

Metabolic Heat Production
Steep Uphill & Downhill Slopes

Estimating Energy Expenditure during Level, Uphill, and Downhill Walking

DAVID P. LOONEY[1], WILLIAM R. SANTEE[1,2], ERIC O. HANSEN[1,2], PETER J. BONVENTRE[3], CHRISTOPHER R. CHALMERS[1,2], and ADAM W. POTTER[1]

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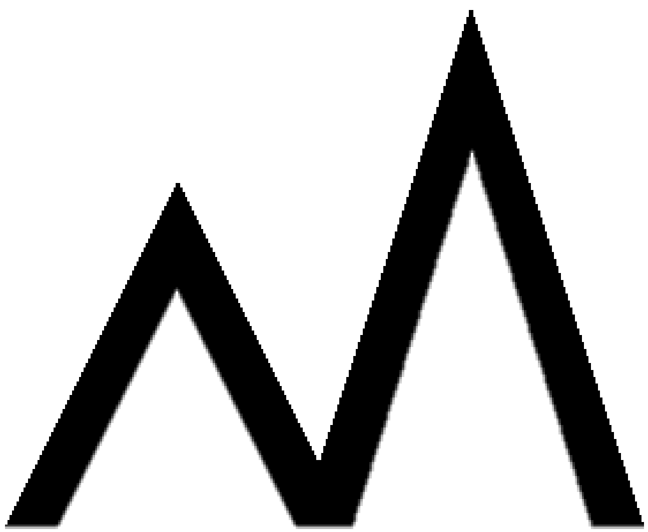
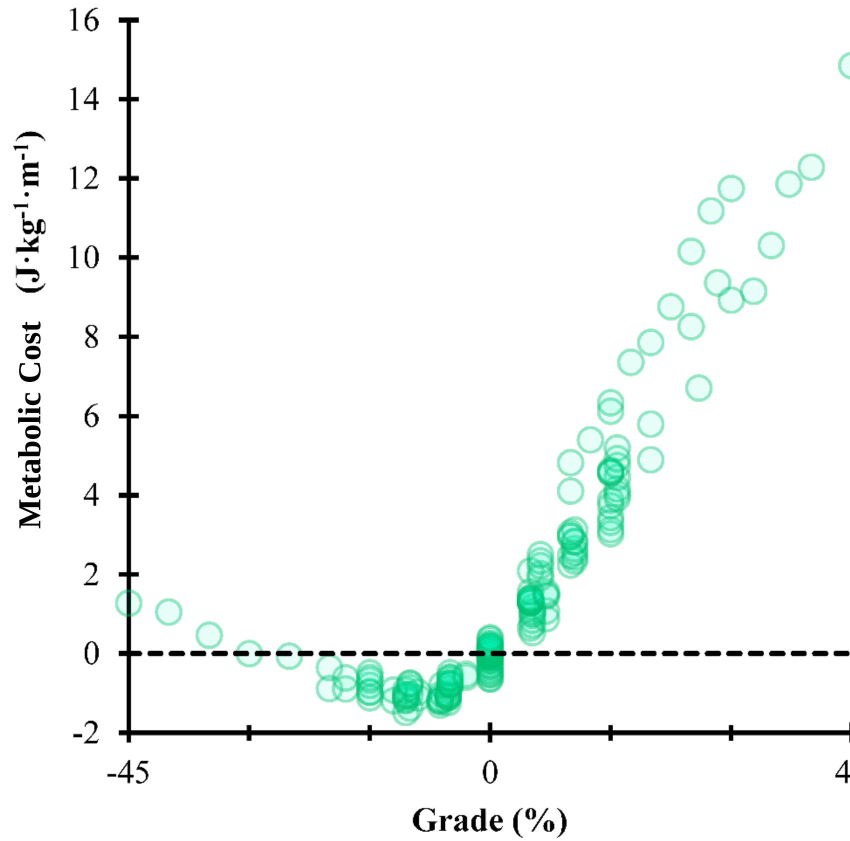




[Looney, et al., 2019]

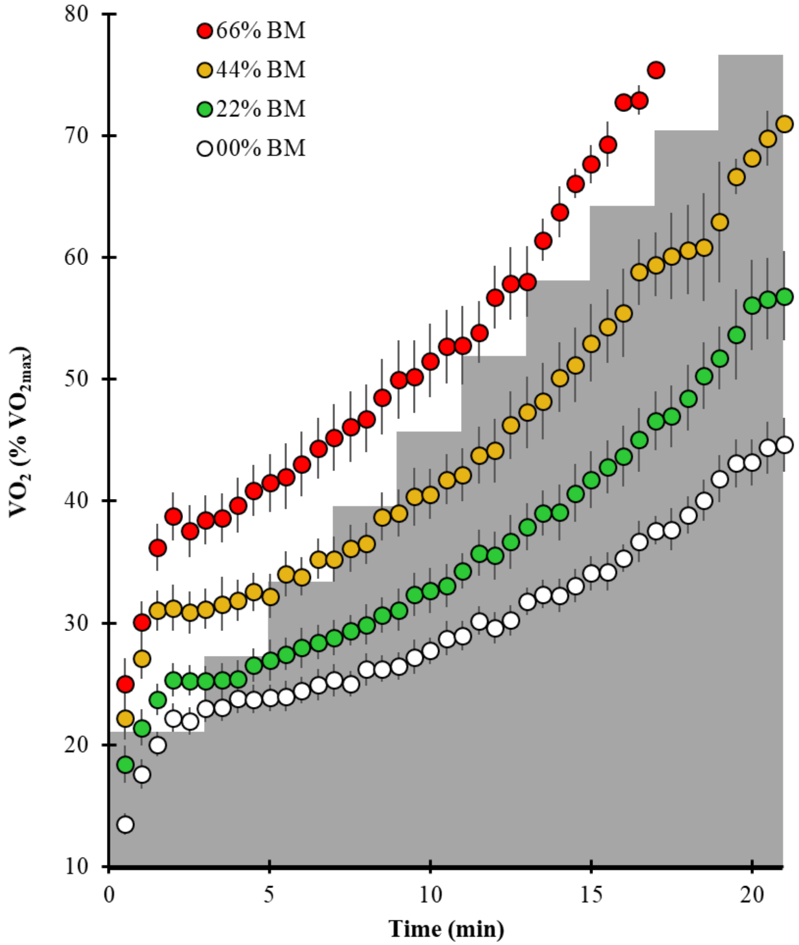
Metabolic Heat Production
Equipment Load

Effects of modern military equipment loads on the maneuverability and metabolism of US Army Soldiers

David P. Looney, Elizabeth M. Doughty, Peter S. Figueiredo, Sai V. Vangala, J. Luke Pryor, William R. Santee, Holly L. McClung, Adam W. Potter.

Under Journal Review

Photo by U.S. Army/Mr. David Kamm (RDECOM)
https://www.tactical-life.com/news/us-army-molle-4000-rucksack/

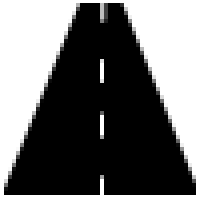


Metabolic Heat Production
Difficult Terrain

TERRAIN FACTORS FOR PREDICTING WALKING AND LOAD CARRIAGE ENERGY COSTS: REVIEW AND REFINEMENT

Richmond PW[1], Potter AW[2], Santee WR[2]

JOURNAL OF SPORT AND HUMAN PERFORMANCE



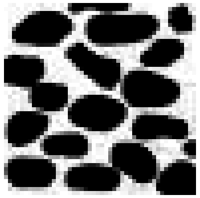


Table 11. Recommended Values for η for use in eq 8.

Terrain Description	η	Comments
Rough Terrain	unknown	Assume surface roughness affect is embedded in the η selected for the terrain.
Slippery Terrain	1.7	Hard wet clay, ice
Vegetation	$\eta = 0.0718V^3 + 1.3V^2 - 5.3701V + 6.0705$	
Swamp	3.5	Based on Table 2 and Figure 5 for very low cone index
Paved Roads	1.0	See Table 3, there is variability and possibly a relationship to load and velocity
Gravel Roads	1.2	
"Dirt" Roads	1.2	
Sand	$\eta = 1.5 + \frac{1.3}{V^2}$	See Figure 1, for range of values, weaker sand will have higher values.
Silts and Clays	$\eta = 1.0 + \frac{2.5}{(ConeIndex - 4.8)}$ for $ConeIndex \geq 7$	For Cone Index ≤ 7 assume it is a swamp

[Richmond, et al., 2015; 2019]

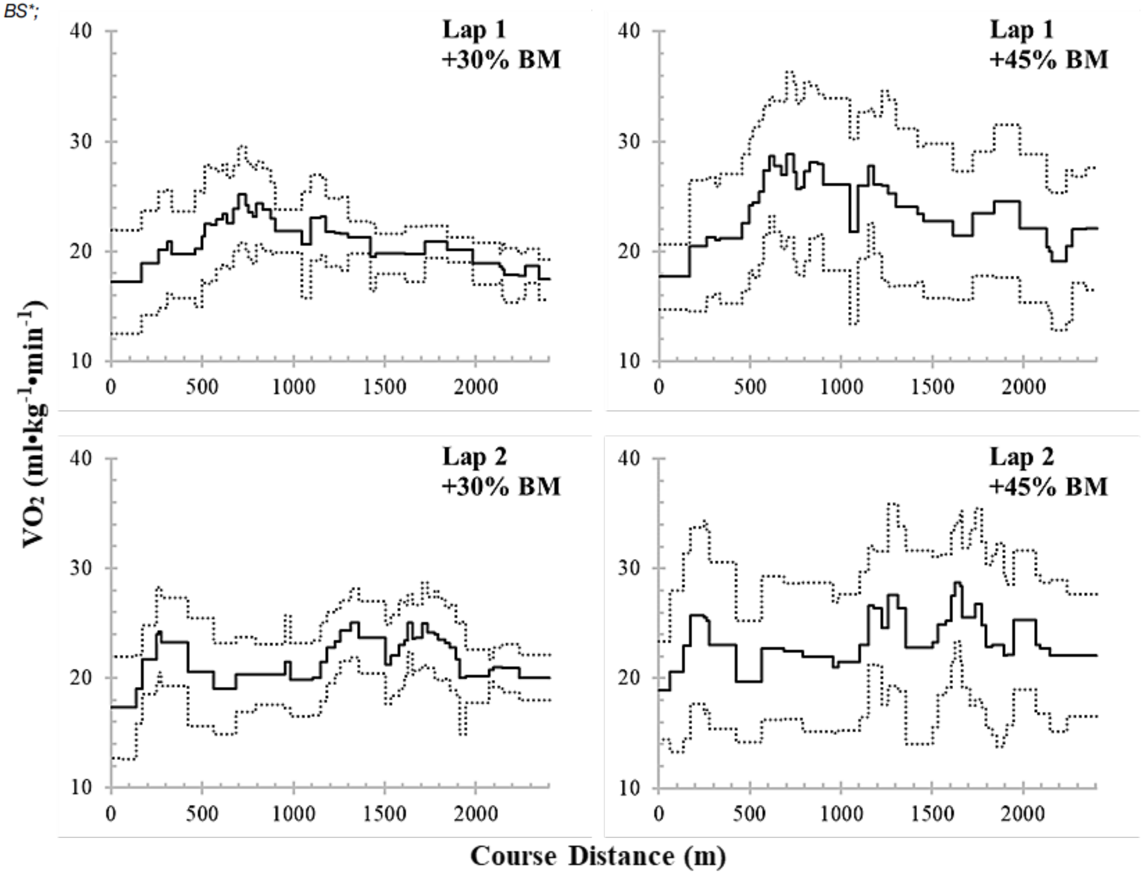
Metabolic Heat Production

Complex Terrain

Metabolic Costs of Military Load Carriage over Complex Terrain

David P. Looney, PhD*†; William R. Santee, PhD*†; Anthony J. Karis, BS*; Laurie A. Blanchard, BS*; Maxwell N. Rome, BA*†; Alyssa J. Carter*; Adam W. Potter, MS*

MILITARY MEDICINE



[Looney, et al., 2018]

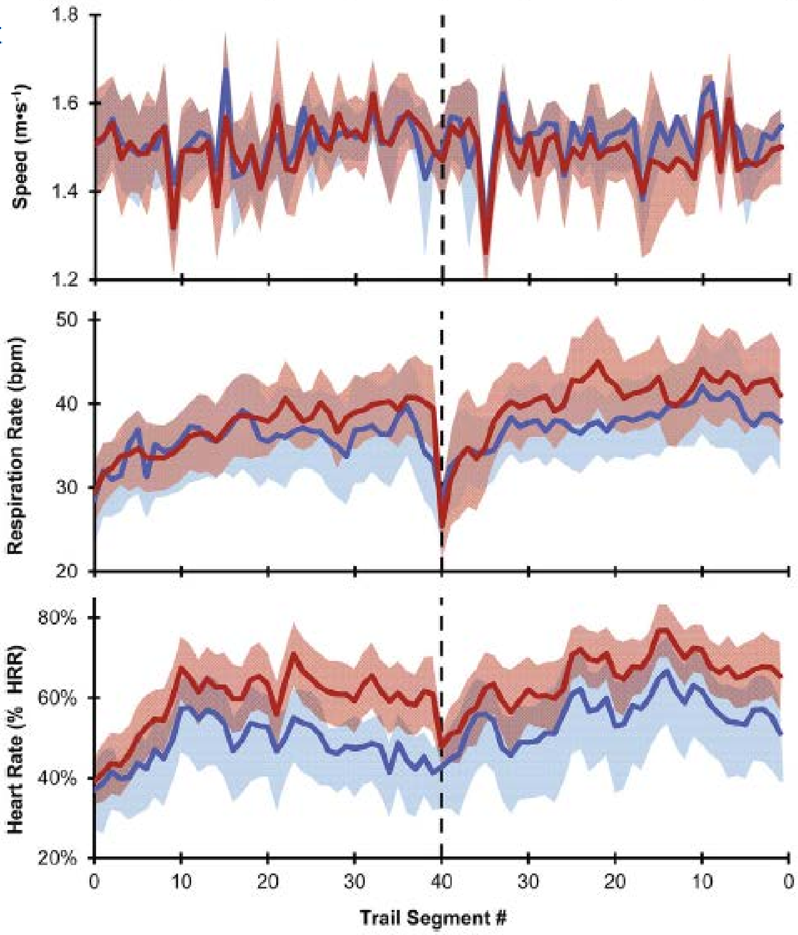
Metabolic Heat Production
Cardiovascular Strain

Cardiorespiratory responses to heavy military load carriage over complex terrain☆

David P. Looney[a,*], William R. Santee[a,b], Laurie A. Blanchard[a], Anthony J. Karis[a], Alyssa J. Carter[a], Adam W. Potter[a]

Applied Ergonomics 73 (2018) 194–198

[Looney, et al., 2018]

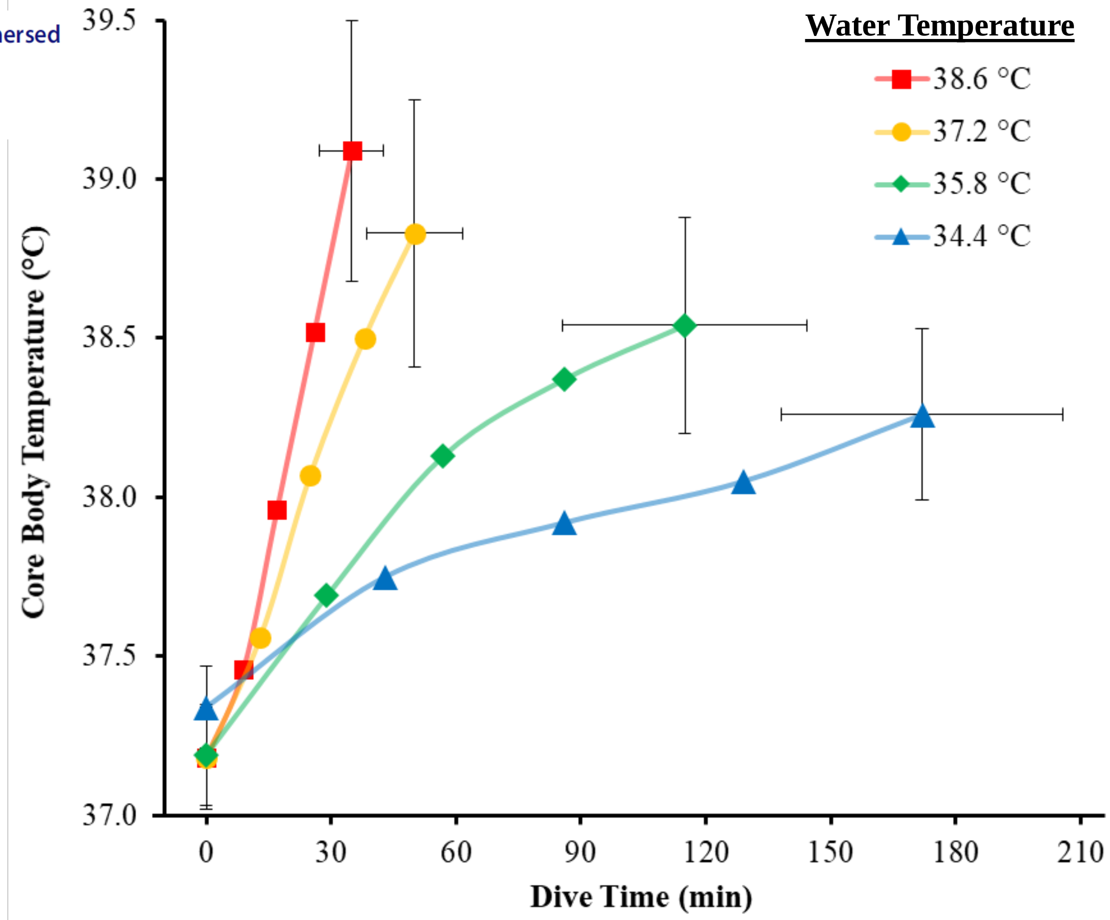


Metabolic Heat Production
Extreme Environments

Divers risk accelerated fatigue and core temperature rise during fully-immersed exercise in warmer water temperature extremes

David P. Looney[a], Edwin T. Long[b], Adam W. Potter[a,c], Xiaojiang Xu[a], Karl E. Friedl[a], Reed W. Hoyt[a], Christopher R. Chalmers[a,d], Mark J. Buller[a], and John P. Florian[b]

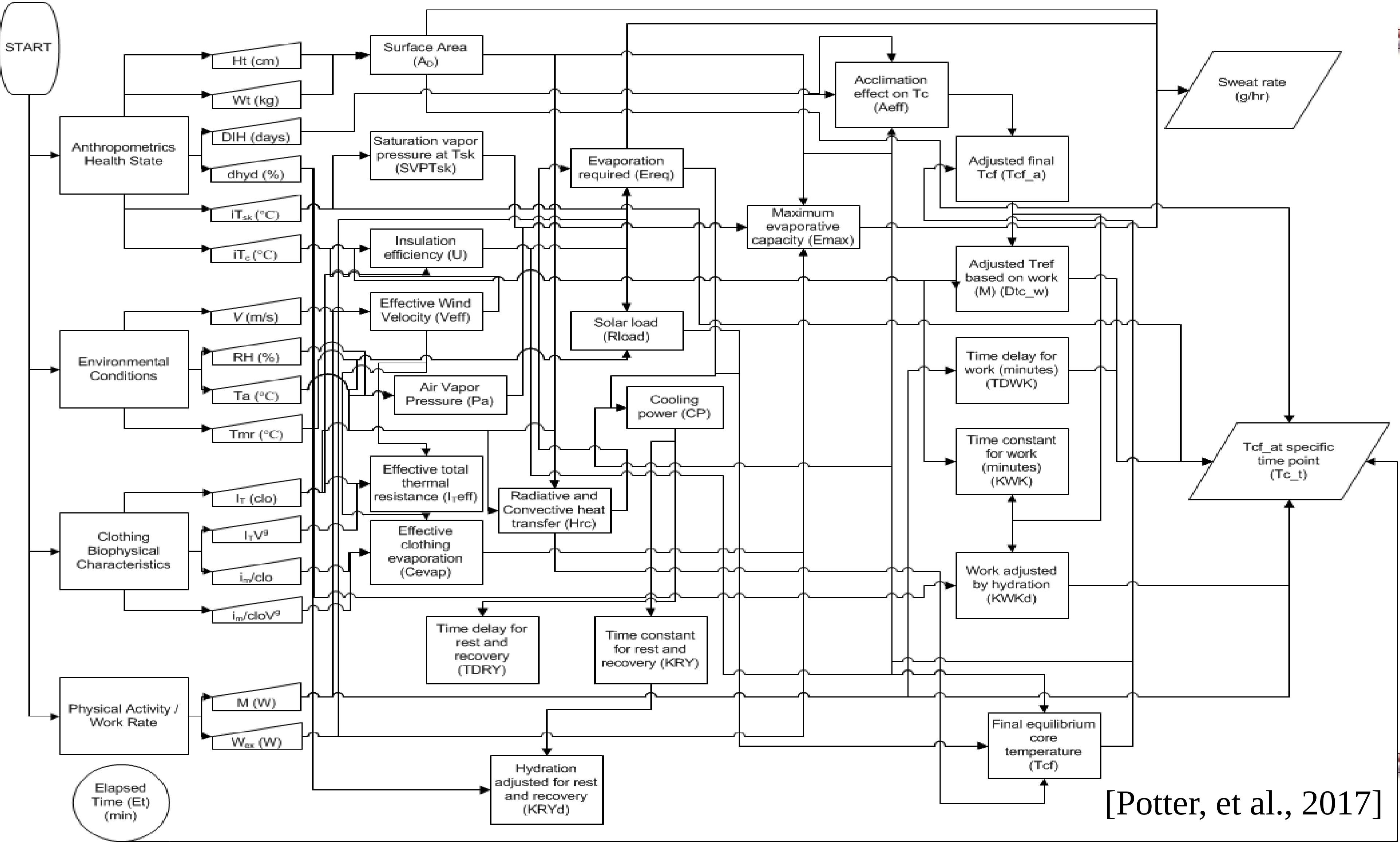
TEMPERATURE
https://doi.org/10.1080/23328940.2019.1599182



[Looney, et al., 2019]

Heat Stress

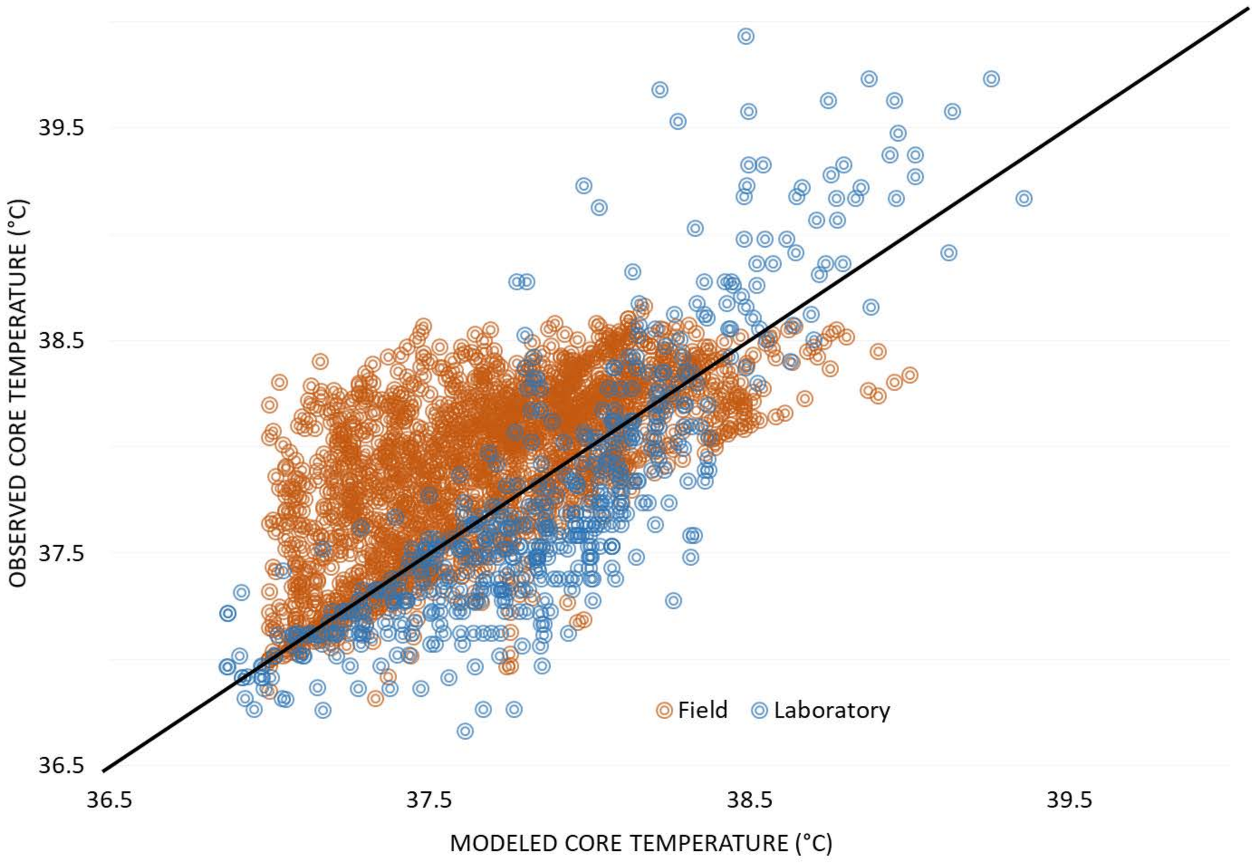
Schematic of the Heat Strain Decision Aid (HSDA)



[Potter, et al., 2017]

Validation

Heat stress [Assessment 1] – Individual
2 Studies (Lab and Field);
Chemical Protective Clothing,
N = 28



[Potter, et al., 2019]

Validation

Heat stress [Assessment 1] – Individual

2 Studies (Lab and Field); Chemical Protective Clothing, N = 28

Environment	Clothing	*Observed T_c*	Bias	MAE	RMSE
Laboratory	L1	37.64 ± 0.55	-0.15 ± 0.26	0.23 ± 0.20	0.30 ± 0.13
	L2	37.75 ± 0.64	-0.14 ± 0.34	0.29 ± 0.24	0.38 ± 0.20
	L3	37.88 ± 0.70	0.03 ± 0.42	0.31 ± 0.28	0.42 ± 0.33
	Total	37.76 ± 0.64	-0.10 ± 0.36	0.28 ± 0.24	0.37 ± 0.24
Field	F1	37.69 ± 0.35	0.22 ± 0.30	0.29 ± 0.24	0.37 ± 0.21
	F2	37.67 ± 0.36	0.21 ± 0.32	0.30 ± 0.24	0.39 ± 0.21
	F3	37.55 ± 0.35	0.36 ± 0.30	0.37 ± 0.28	0.47 ± 0.27
	F4	37.79 ± 0.43	0.13 ± 0.32	0.27 ± 0.23	0.35 ± 0.20
	Total	37.68 ± 0.38	0.23 ± 0.32	0.30 ± 0.25	0.40 ± 0.25
Collective Total	**L1-L3 F1-F4**	37.69 ± 0.45	0.16 ± 0.36	0.30 ± 0.25	0.39 ± 0.23

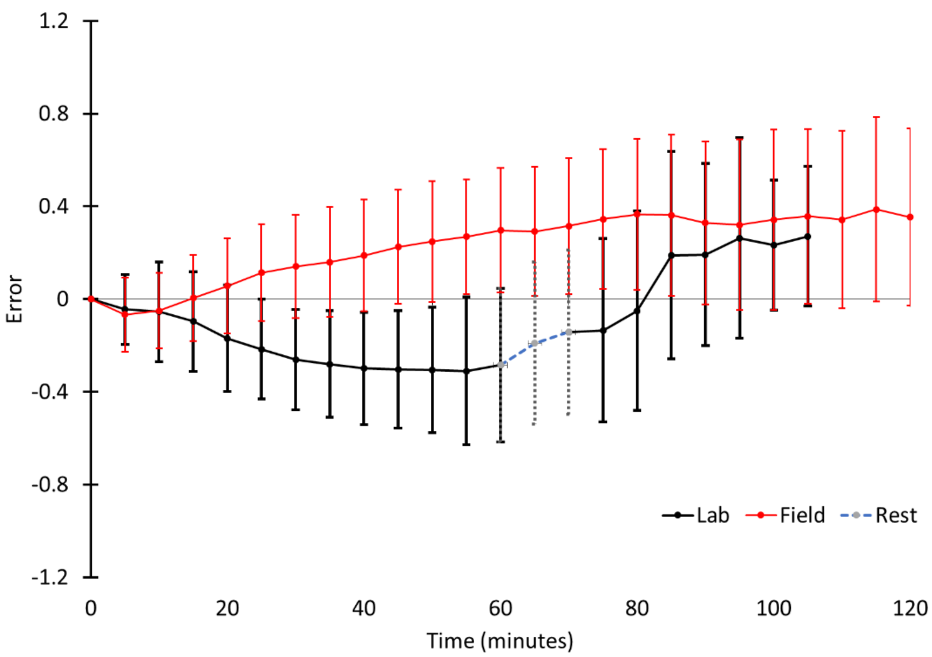
Acceptable bias: ± **0.27°C**

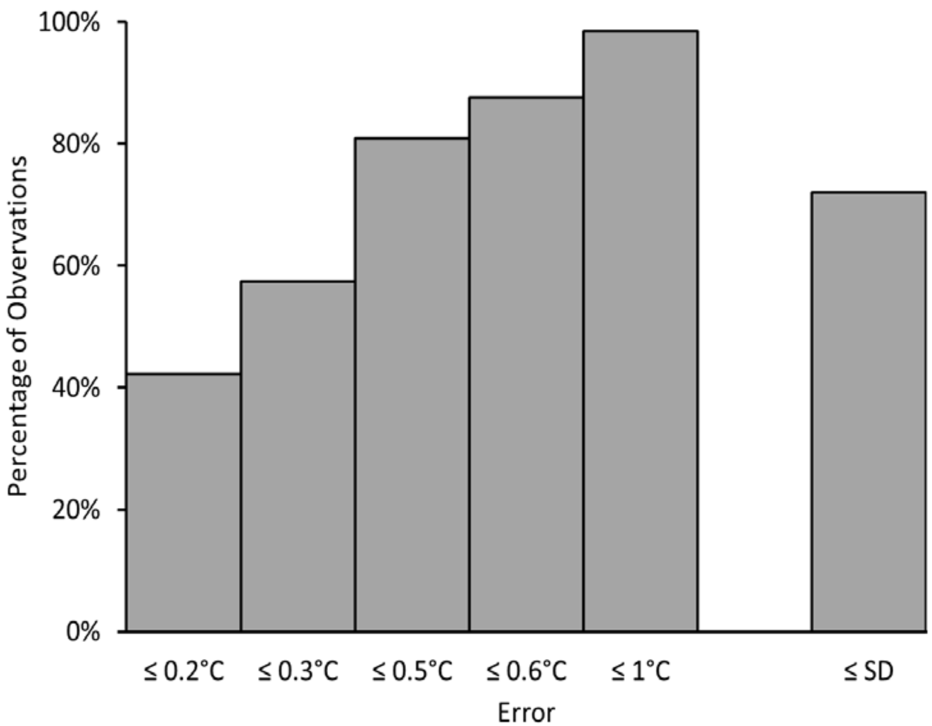
[Potter, et al., 2019]

Validation

Heat stress [Assessment 1] – Individual

2 Studies (Lab and Field); Chemical Protective Clothing, N = 28



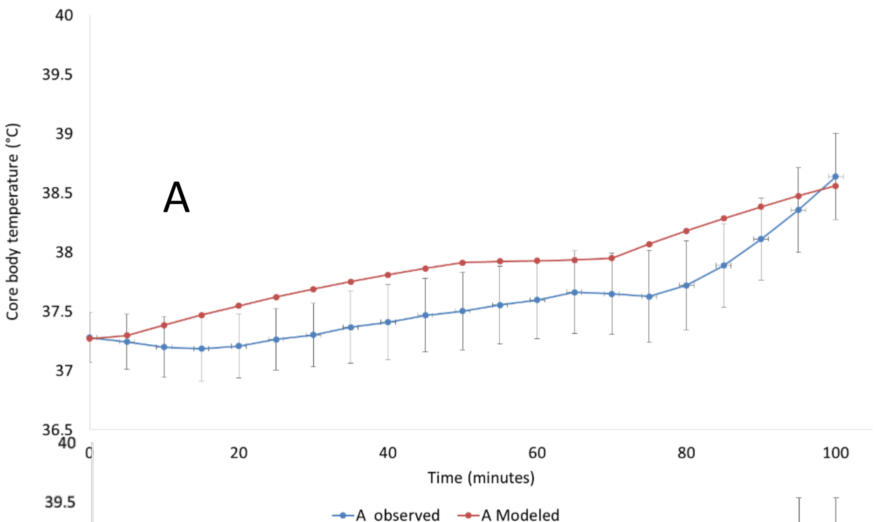


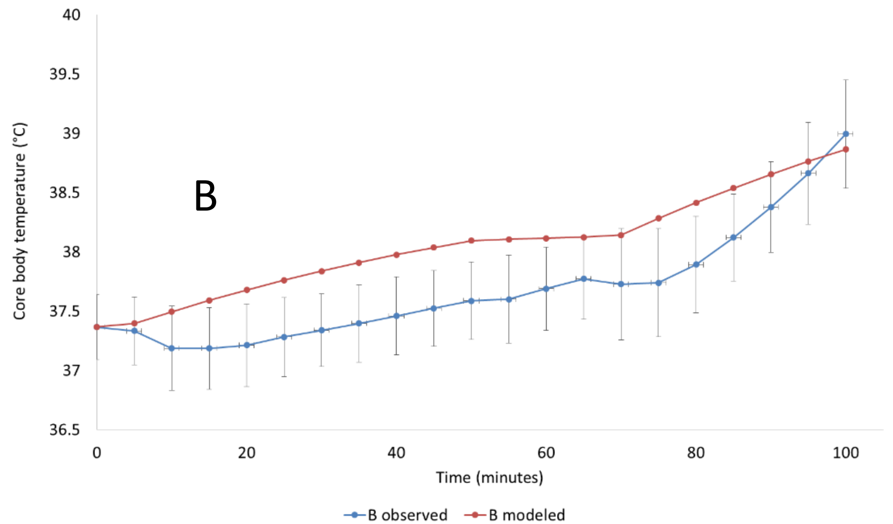
[Potter, et al., 2019]

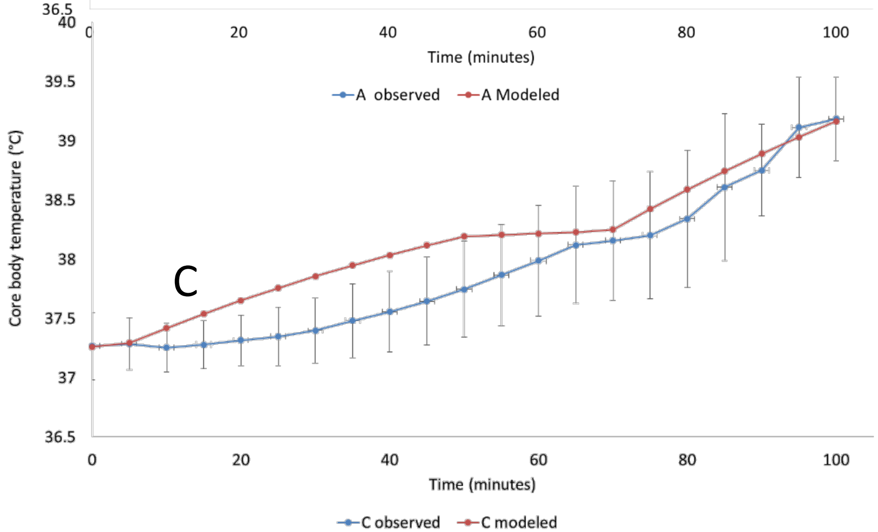
Validation

Heat stress [Assessment 1] – Group Mean

1 Study (Lab); 3 Chemical Protective Clothing ensembles (Human subjects; N = 8)





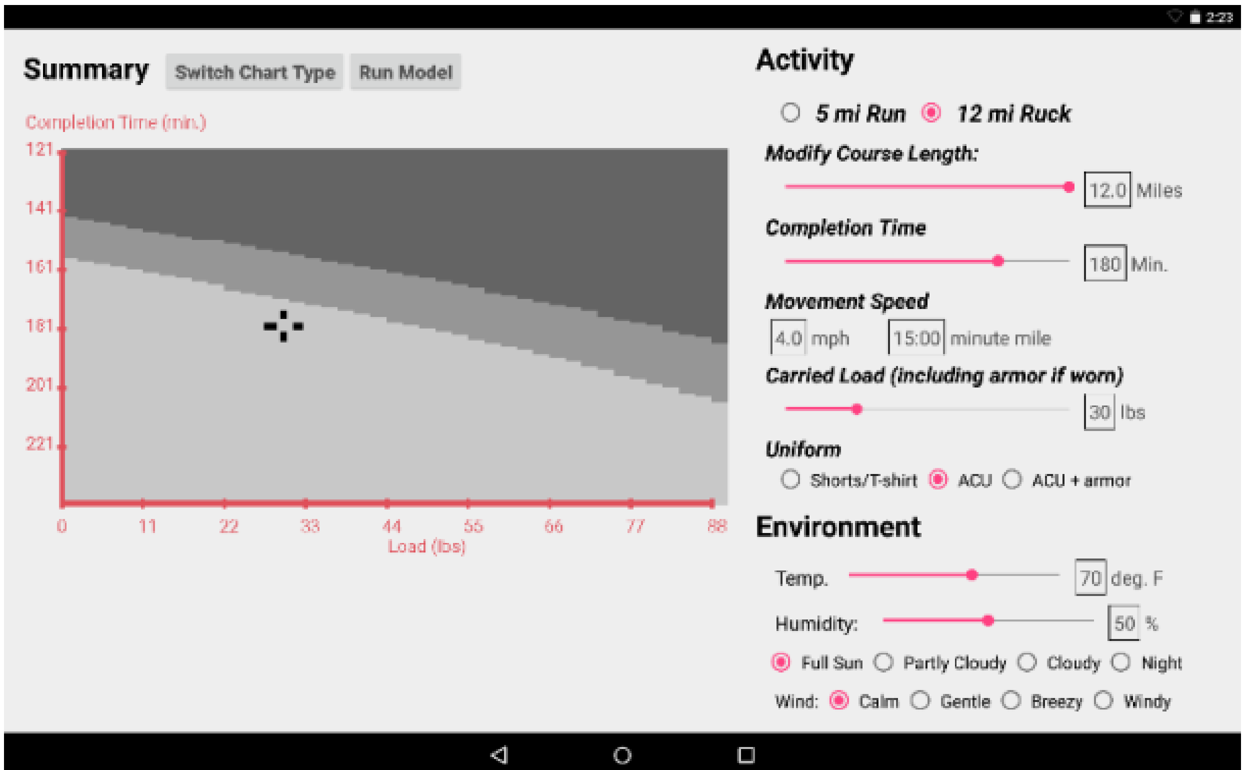


RMSE for each ensemble;
0.70°C for A,
0.37°C for B,
0.25°C for C.

[Potter, et al., 2018]

Heat Strain Decision Aid (HSDA)

Defense Health Agency

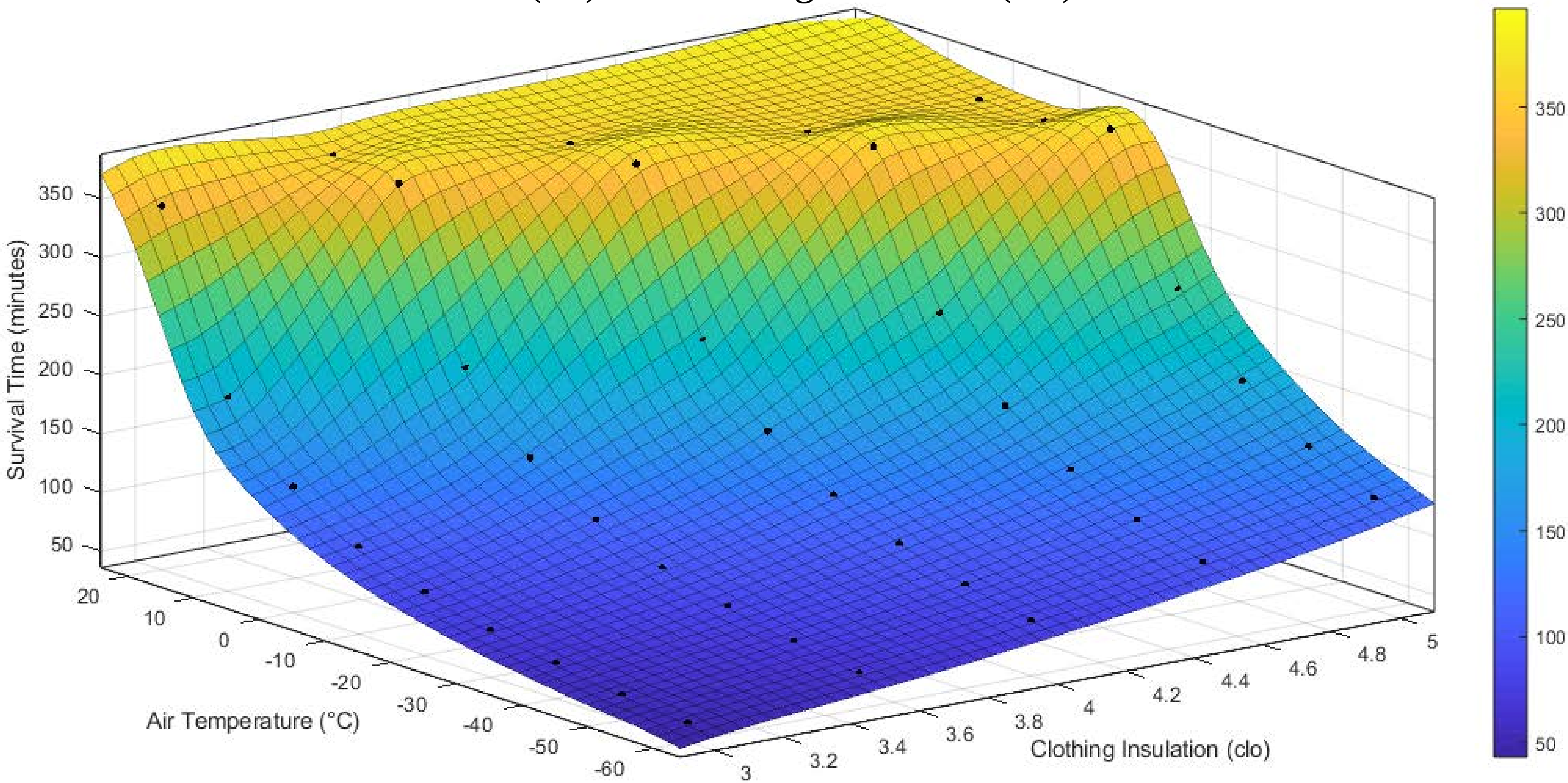


- Empirically based
- For use in materiel developer down-selection or assessment
- Customizable for specific end users

Cold Stress

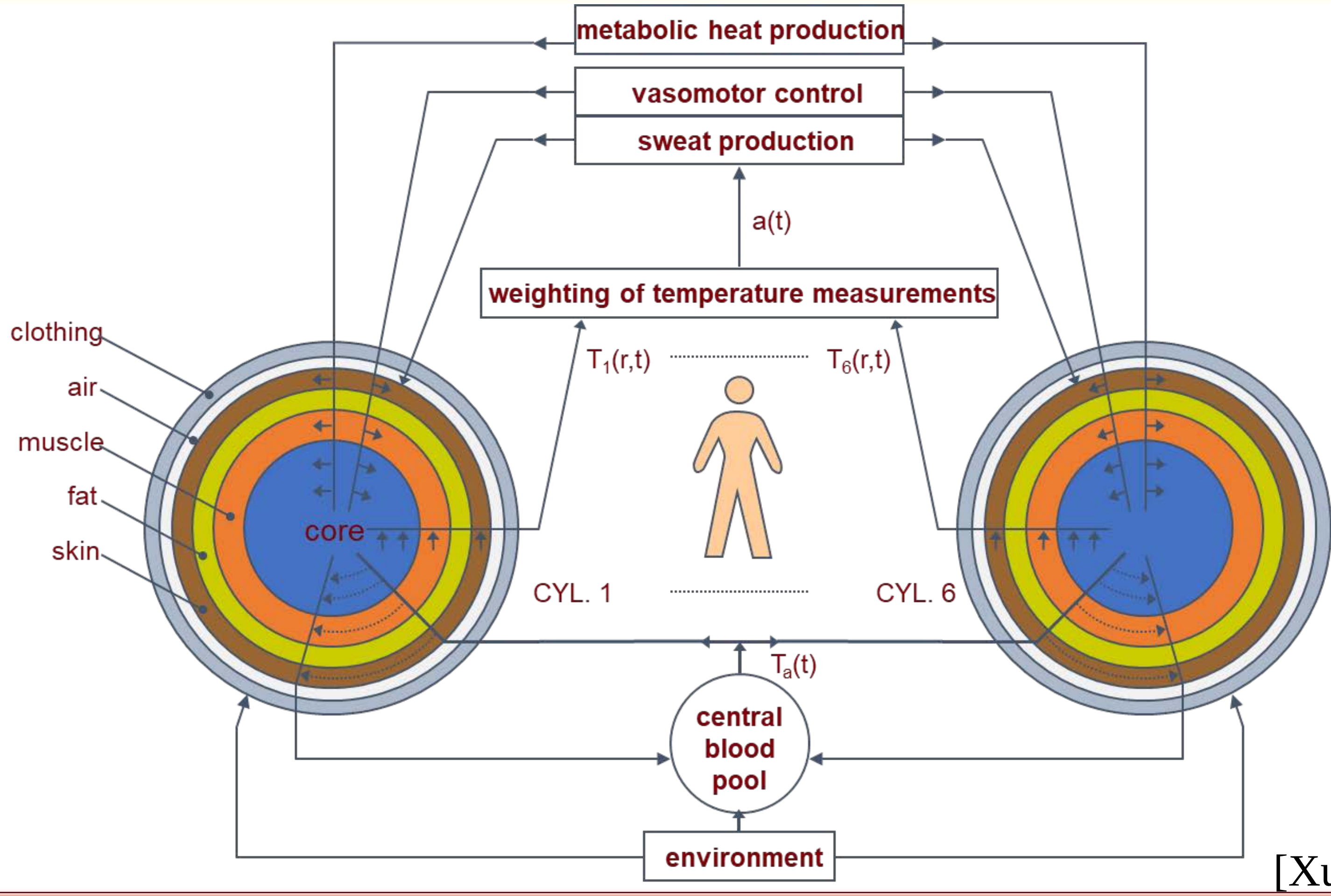
Simplified Modeling of Cold Exposure Survival

Surface plot of survival at rest as a function of air temperature (°C) and clothing insulation (clo)



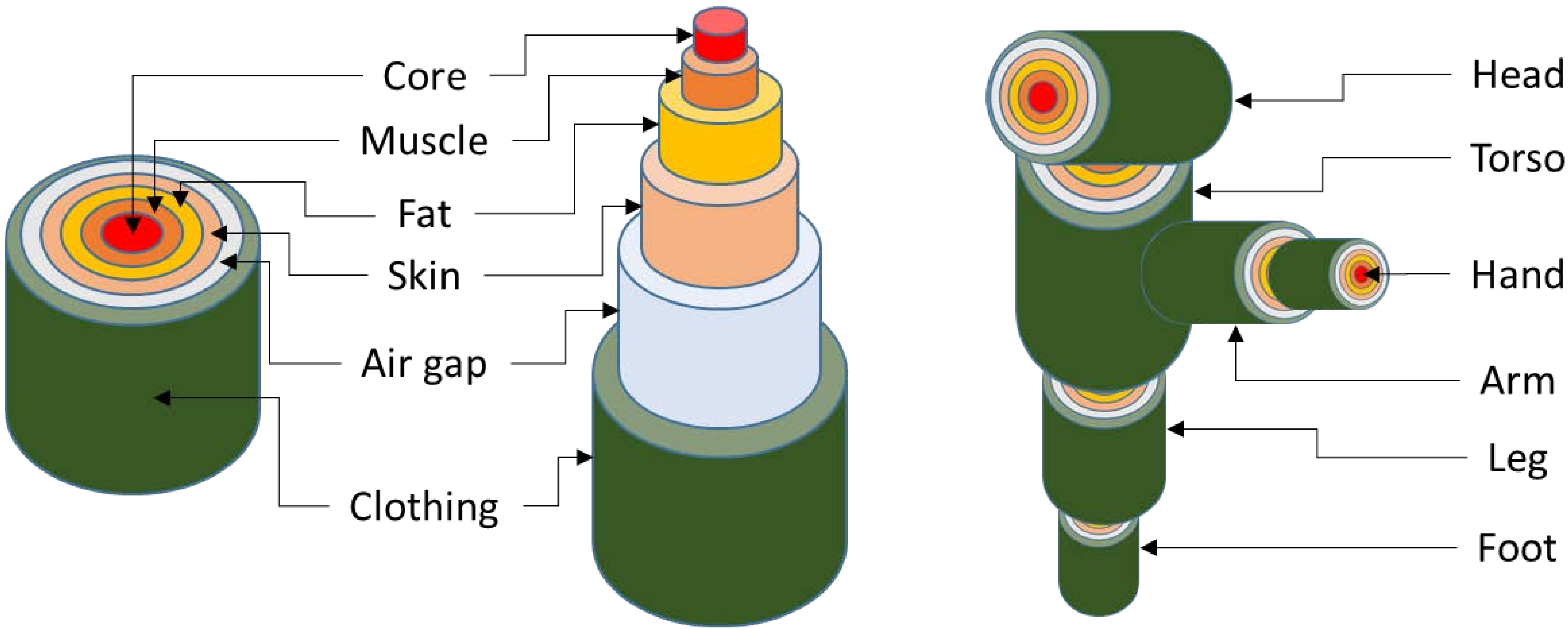
Constructed using data from Santee [1996]

Modeling of Cold Response



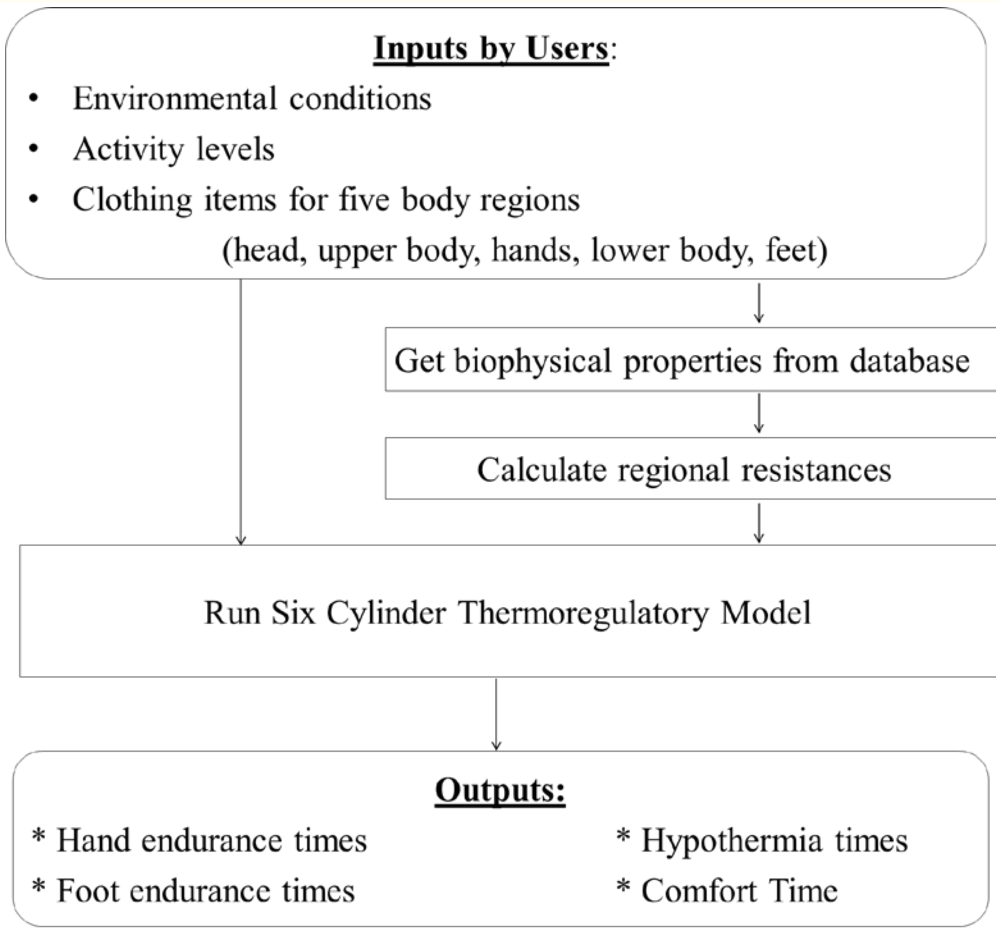
[Xu & Werner, 1997]

Human Representation



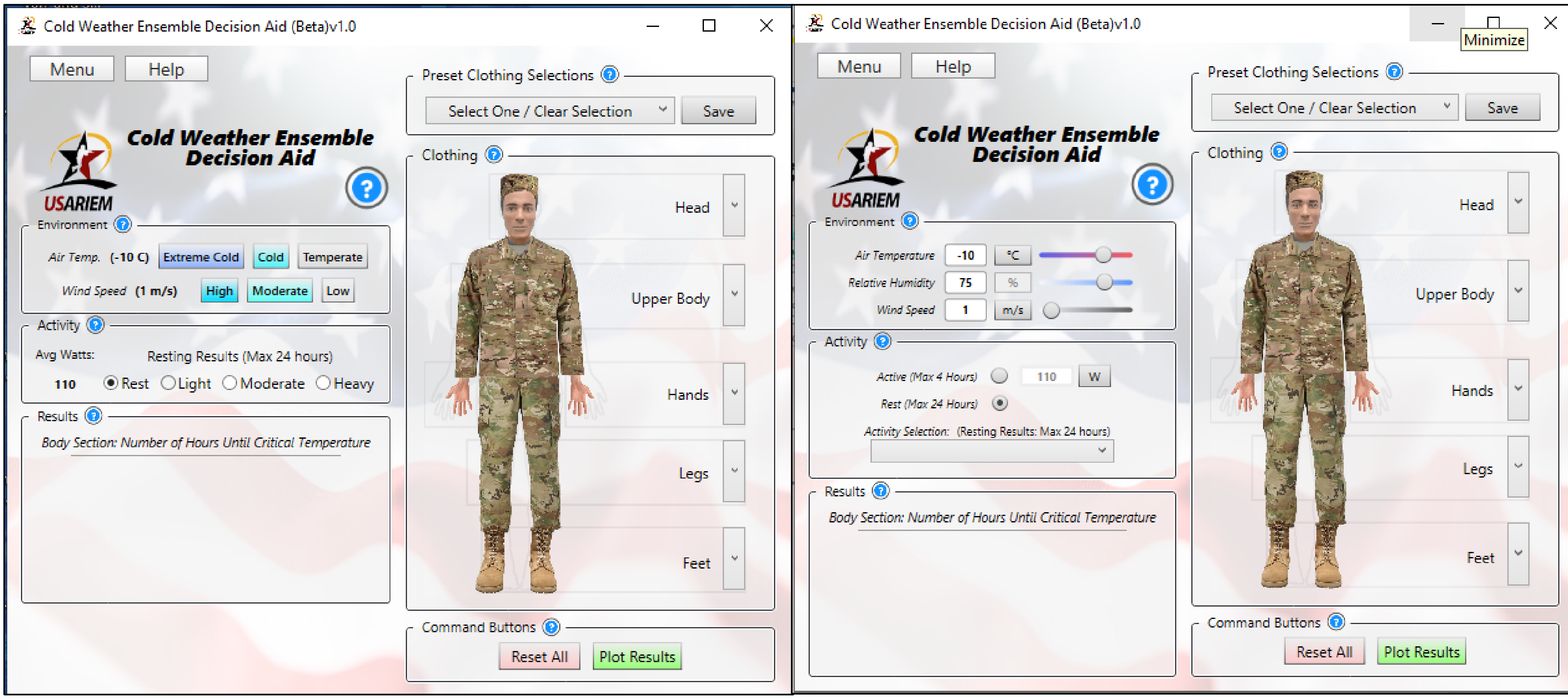
[Potter, et al., 2020b]

Cold Weather Ensemble Decision Aid (CoWEDA)



CoWEDA Displays

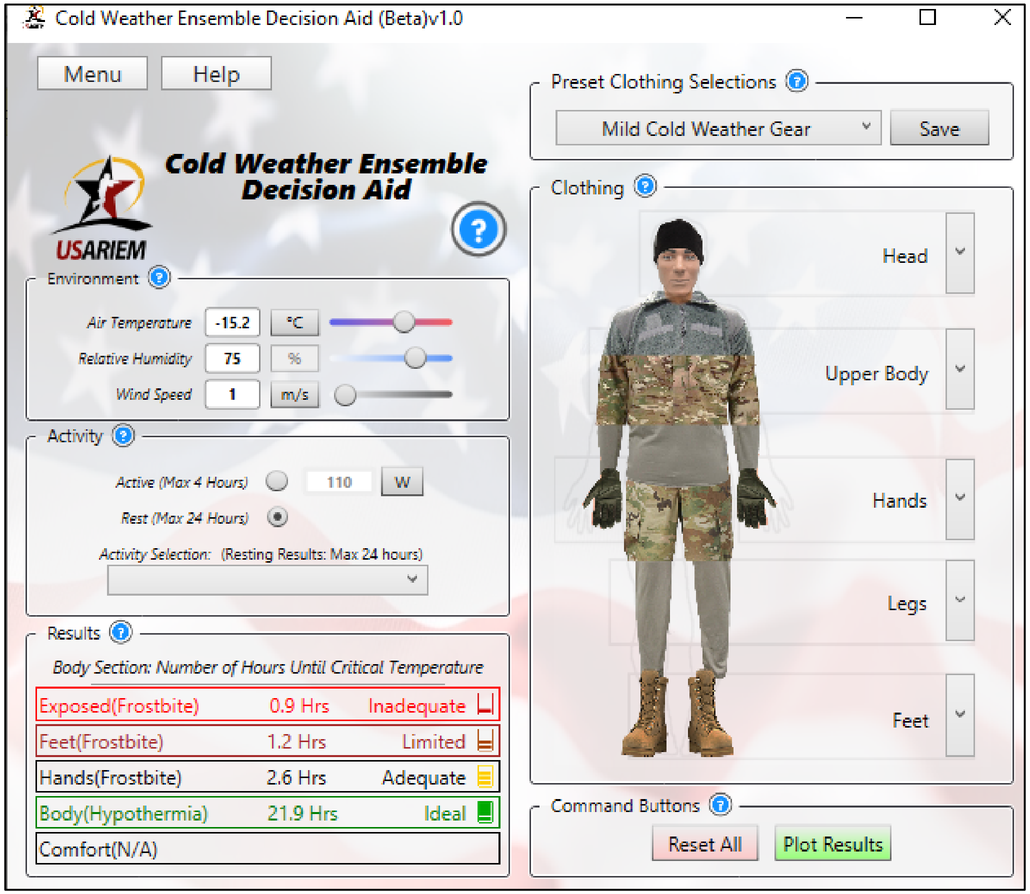
Display can be changed ‘simple’ or ‘advanced’ input views



[Potter, et al., 2020b]

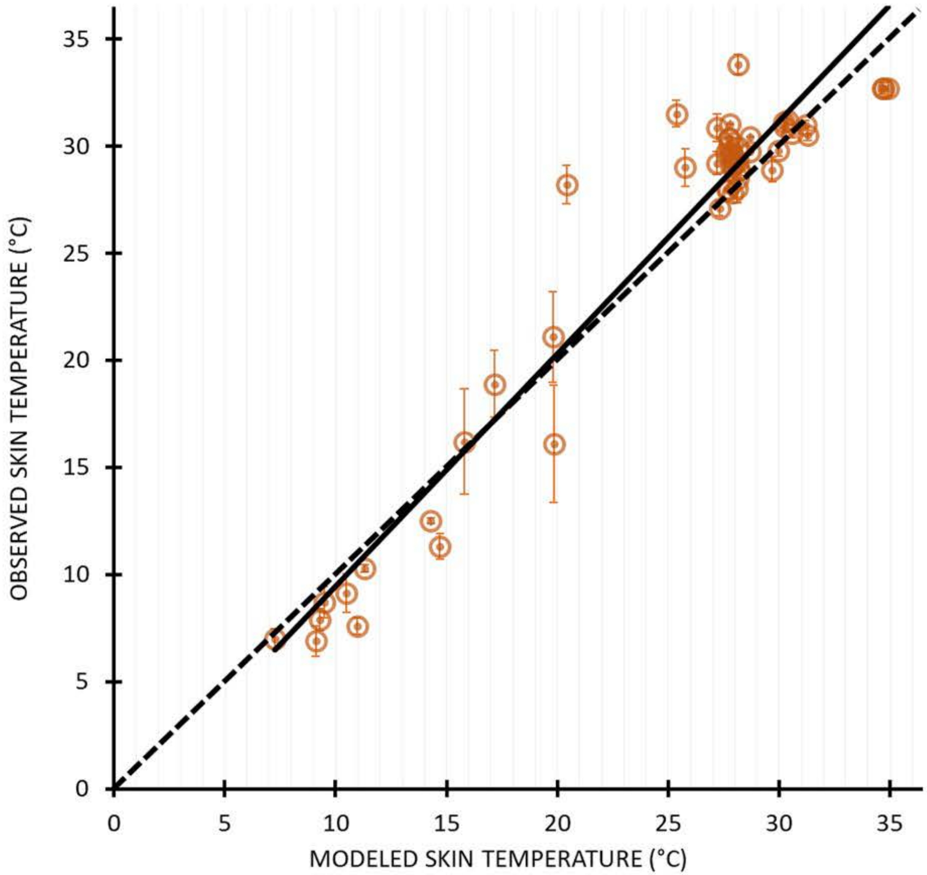
CoWEDA Results

Example Output, where (a) shows the area of outputs or plots can be generated



[Potter, et al., 2020b]

CoWEDA Validation
Predicted skin temperatures



Cold stress [Assessment] – Individual
4 Studies (Lab and Field);
Cold exposure 0 to -40 °C,
N = 23

[Potter, et al., 2020b]

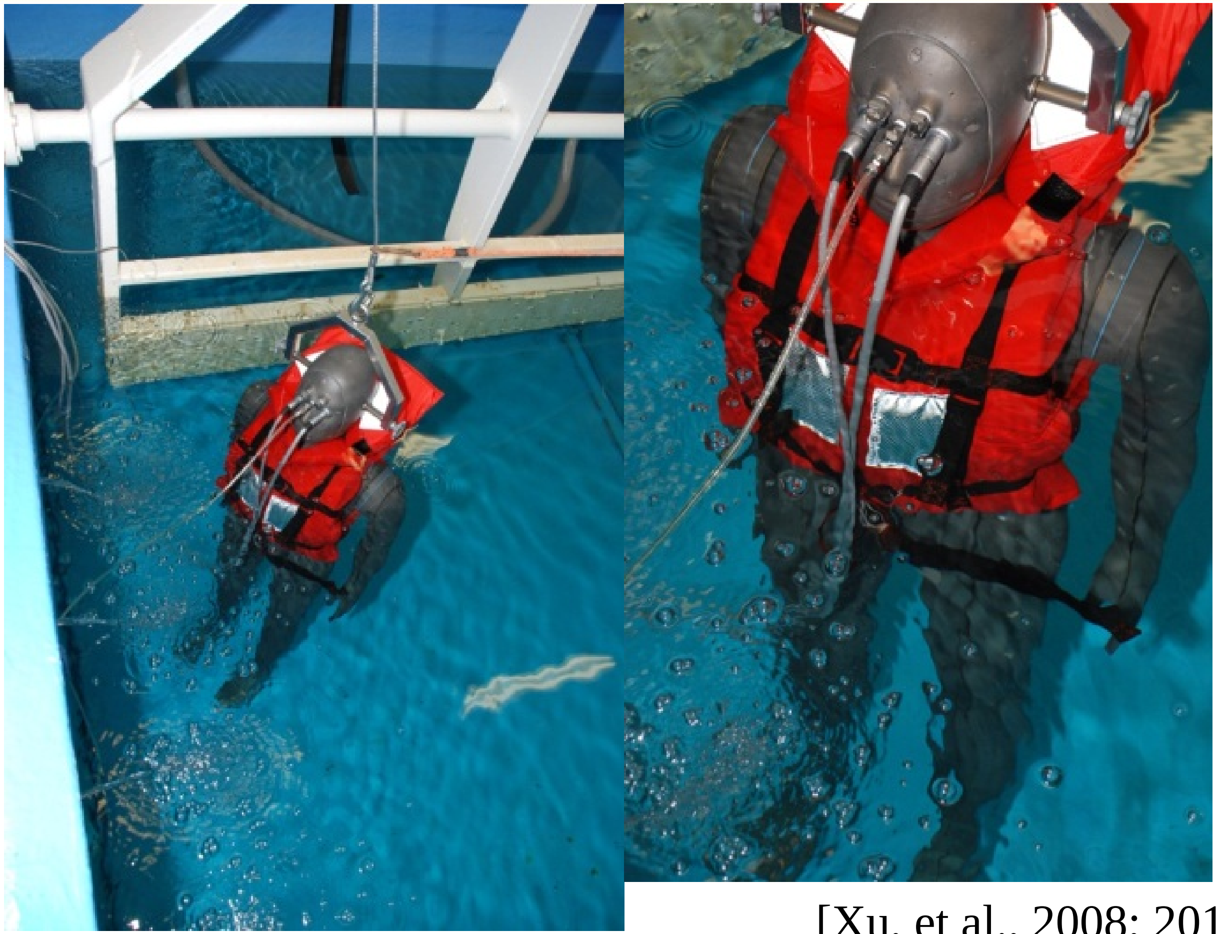
Note: error bars indicate weighted error of group mean data; solid line is linear regression plot

Other Scenarios or Settings…

Extreme highs, lows, and in between…

- Immersion in water…
- Underwater…
- Disabled submarine...
- Enclosed spaces (vehicles, aircrafts, etc.)…
- Subterranean environments…
- High altitude…
- Space…

Probability of Survival Decision Aid (PSDA)

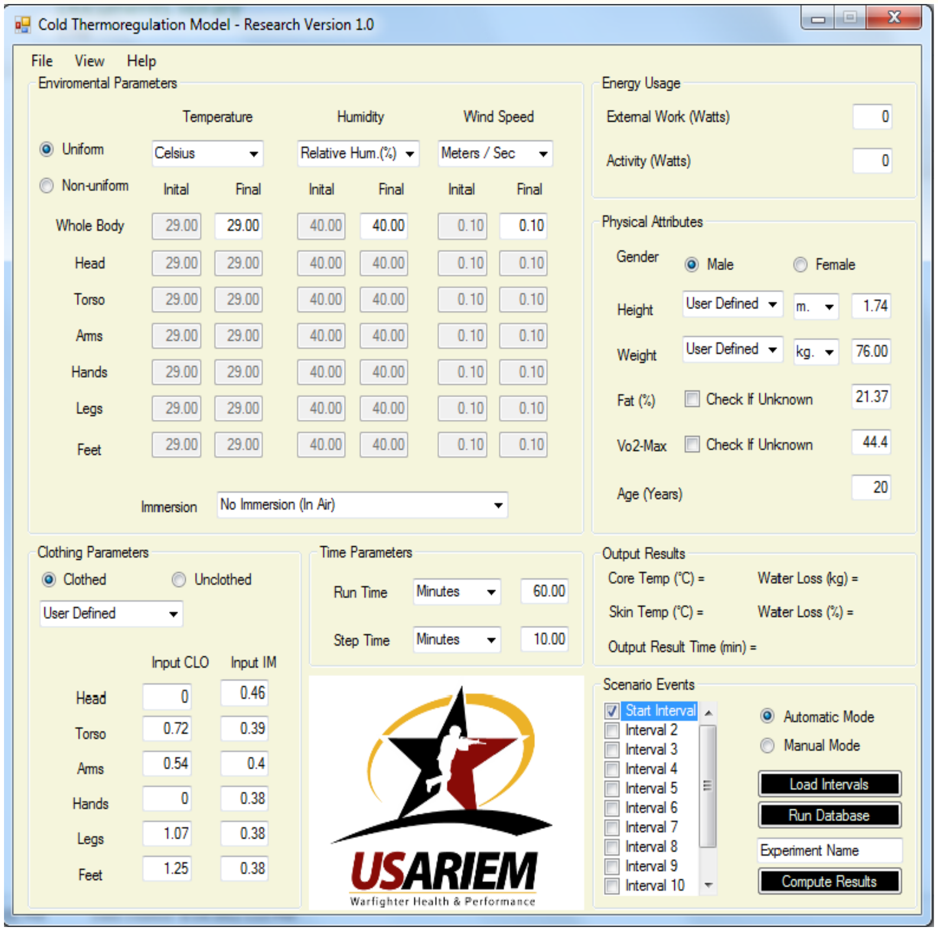


[Xu, et al., 2008; 2014]

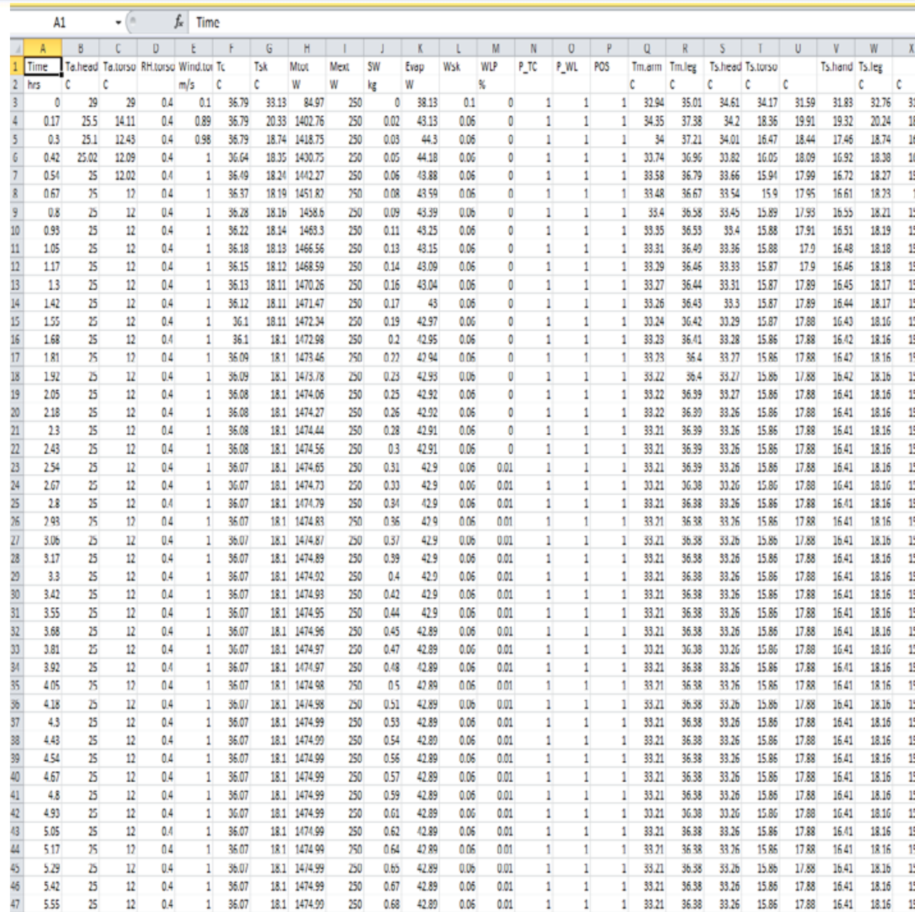
Probability of Survival Decision Aid (PSDA)

Defense Health Agency

Inputs



Outputs

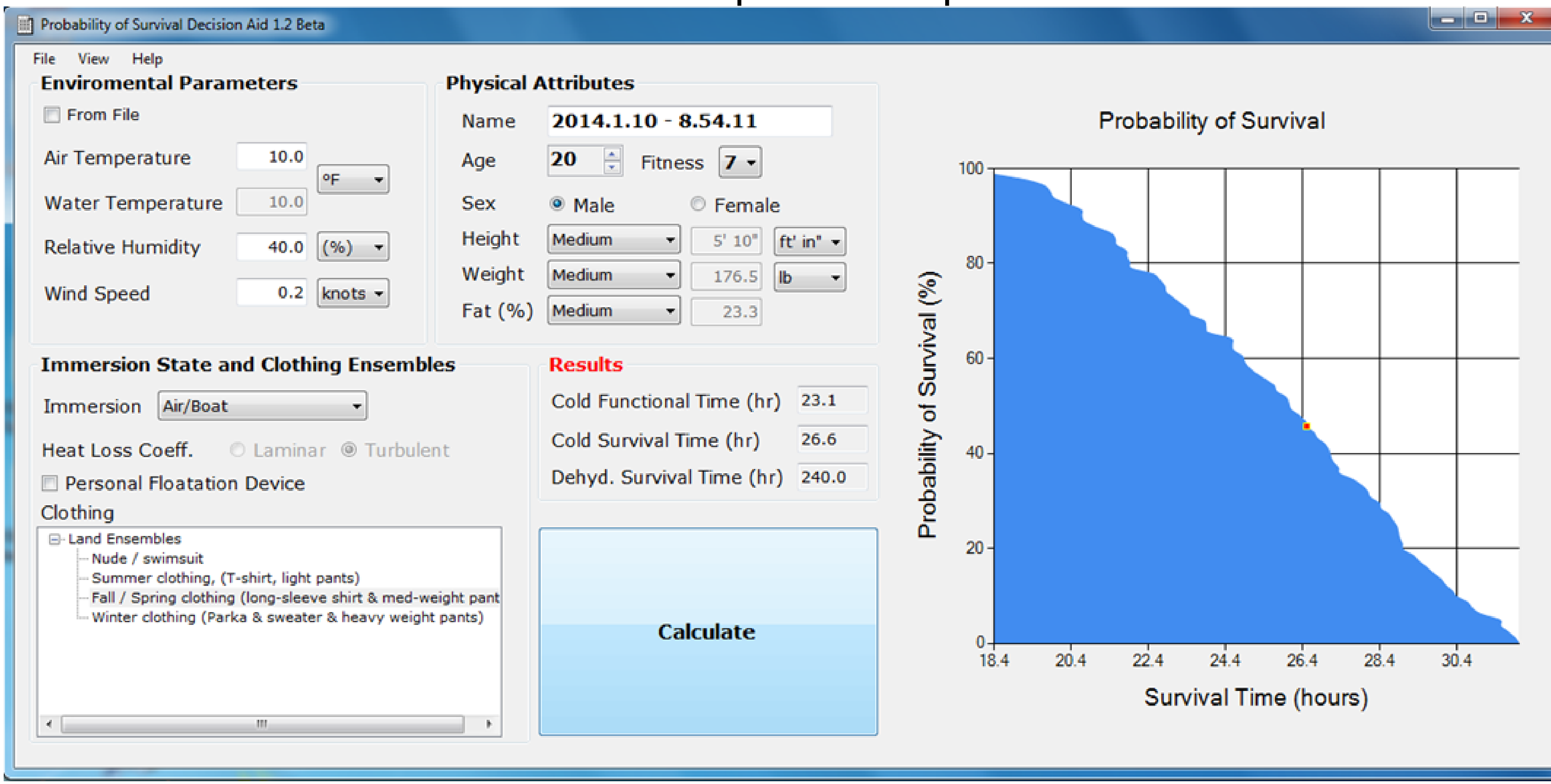


[Xu, et al., 2008; 2014]

"Medically Ready Force…Ready Medical Force"

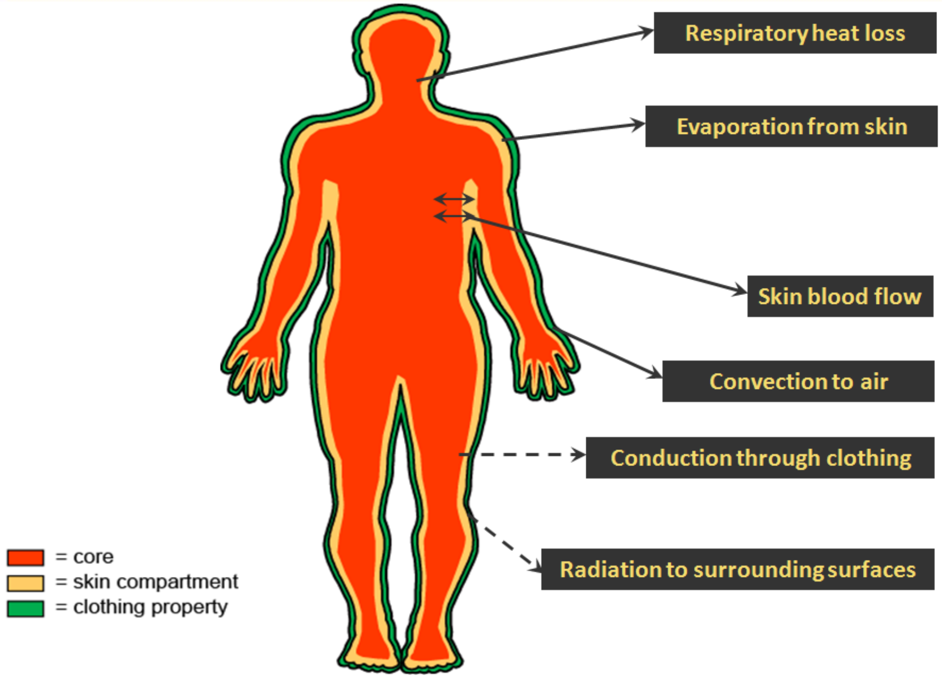
Probability of Survival Decision Aid (PSDA)

PSDA Inputs & Outputs

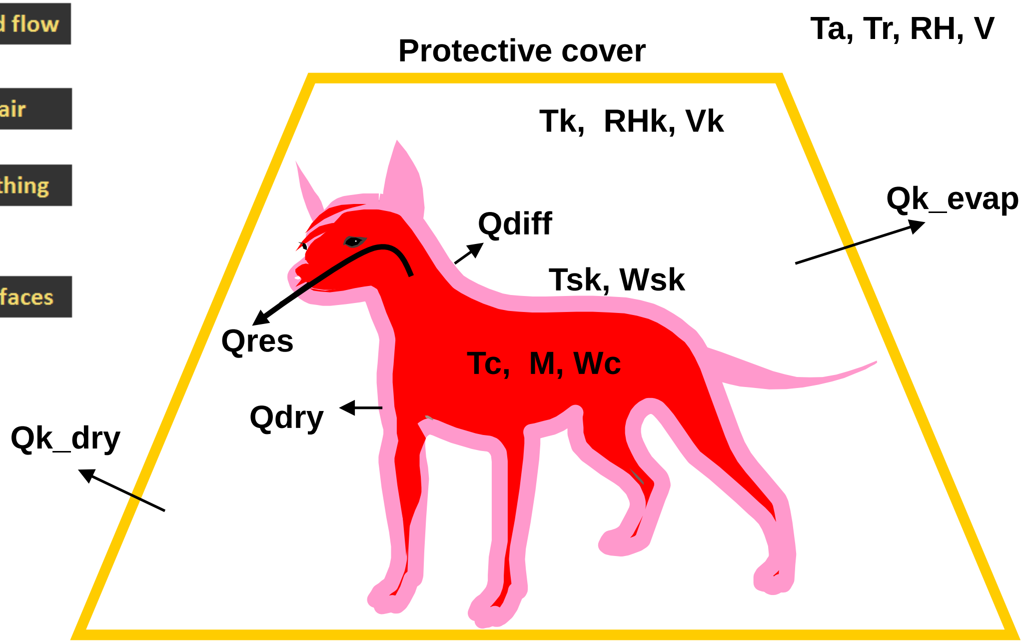


[Xu, et al., 2008; 2014]

Other Species…



[Berglund, et al., 2013]



[Berglund, et al., 2011]

Canine Thermal Model

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A canine thermal model for simulating temperature responses of military working dogs

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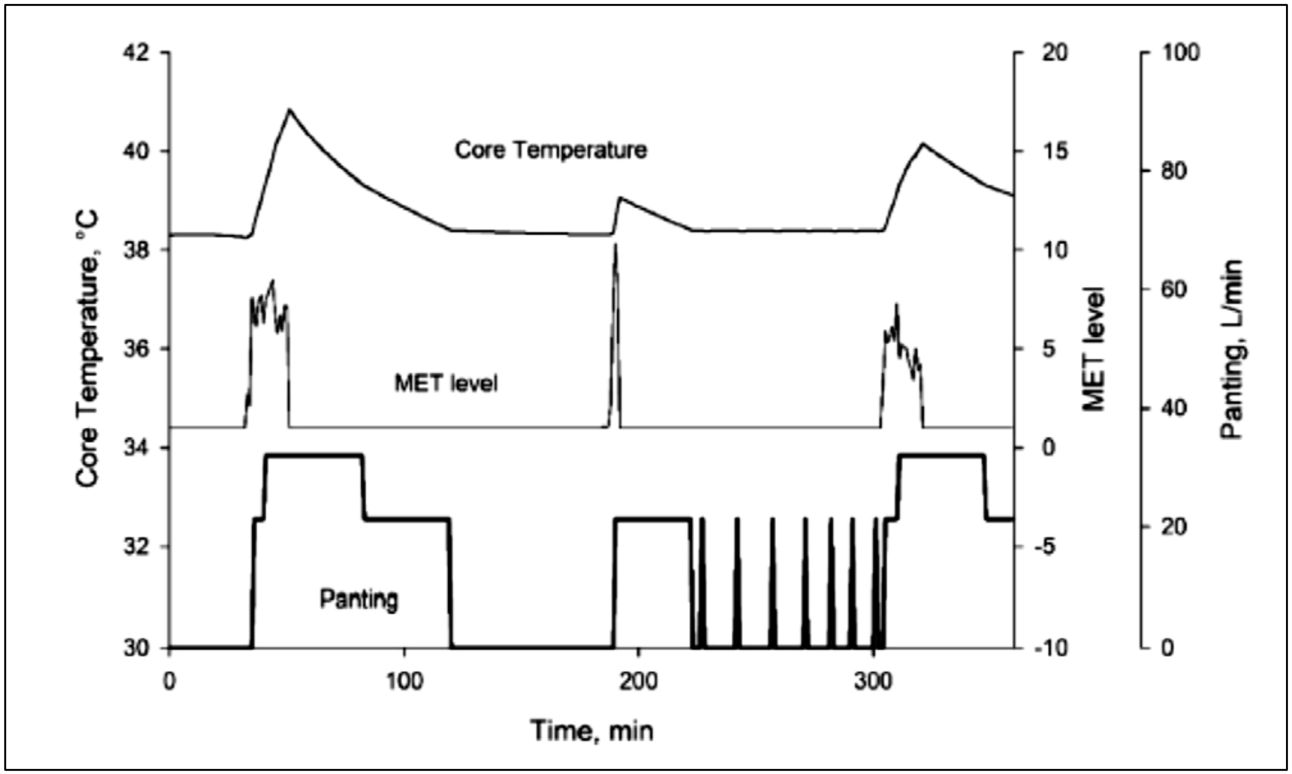
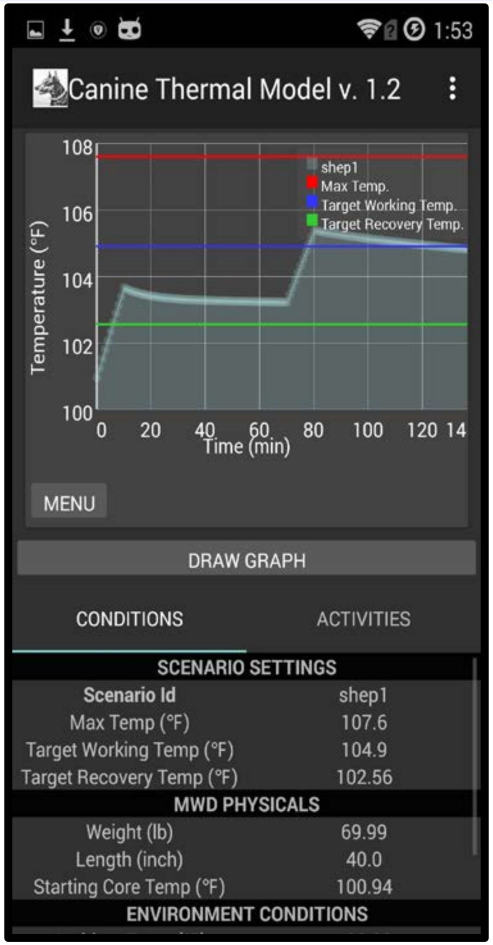
ABSTRACT

Military working dogs (MWDs) are often required to operate in dangerous or extreme environments, to include hot and humid climate conditions. These scenarios can put MWD at significant risk of heat injury. To address this

Canine Thermal Model



[Potter, et al., 2020a]



Key Takeaways

- Heat loss or gain can be effectively modeled when key parameters are known (or estimated).
- Metabolic heat production (e.g., heat produced from work) and clothing properties (insulation / vapor permeability) can significantly influence heat gain or loss.
- Scientifically-based decision aids can be used for risk mitigation, mission planning, and optimization.

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