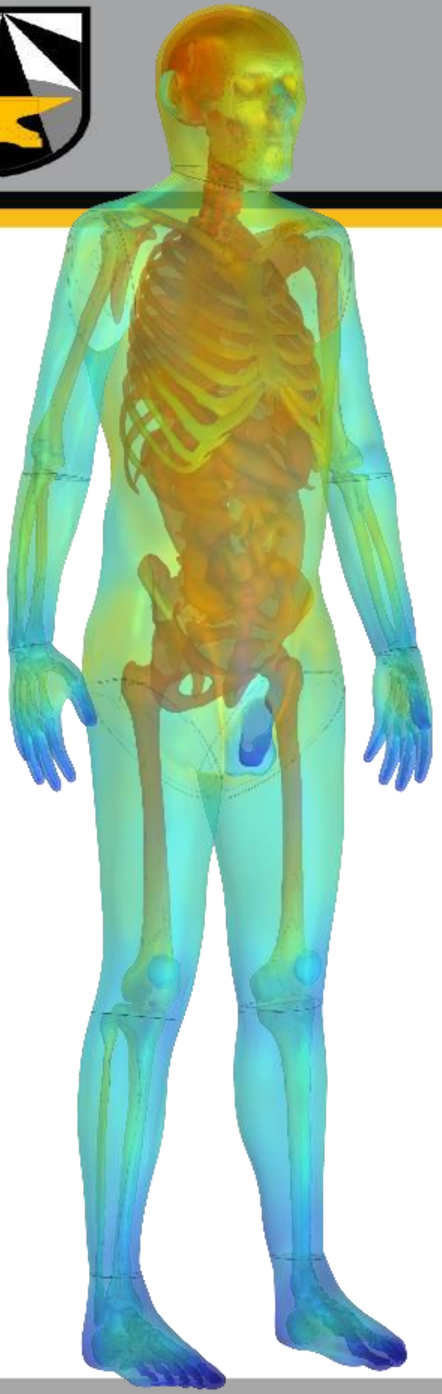

Human Thermoregulation and Spatial Temperature for Frostbite Prediction with COMSOL's Bio-Heat Transfer Module

U.S. Army Research Institute of Environmental Medicine

Thermal and Mountain Medicine Division

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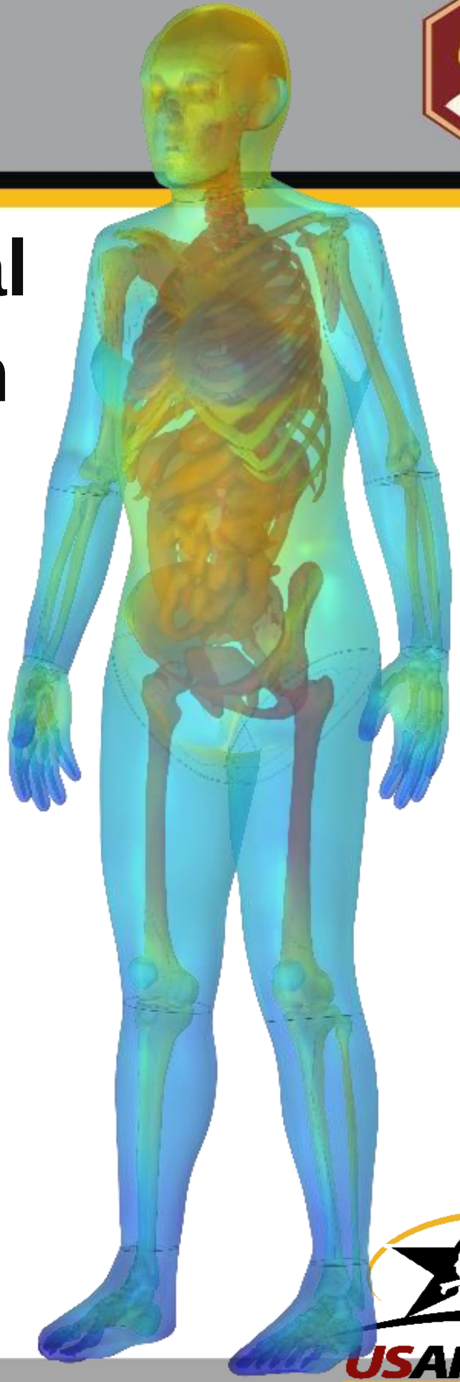

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U.S. Army Research Institute of Environmental Medicine

Thermal and Mountain Medicine Division conducts research to optimize physical and cognitive performance and prevent illness associated with military operations at environmental extremes, such as heat, cold, high terrestrial altitude, and subterranean.

Frostbite and cold injury risk in below freezing ambient temperatures is accelerated by wind.

Find areas of body most susceptible to frostbite.

Methods to reduce frostbite risk.

Predict frostbite risk and exposure time with specific conditions.

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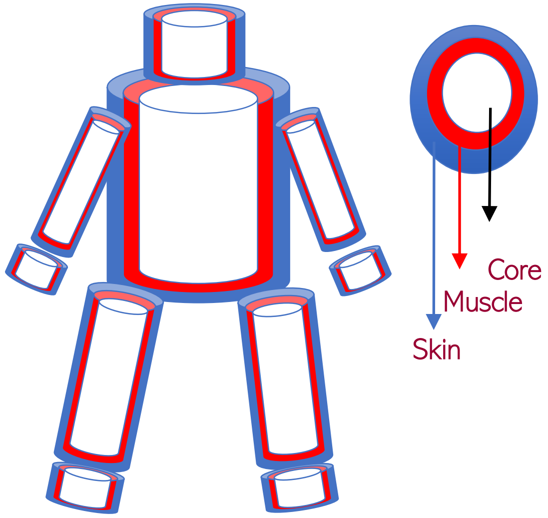
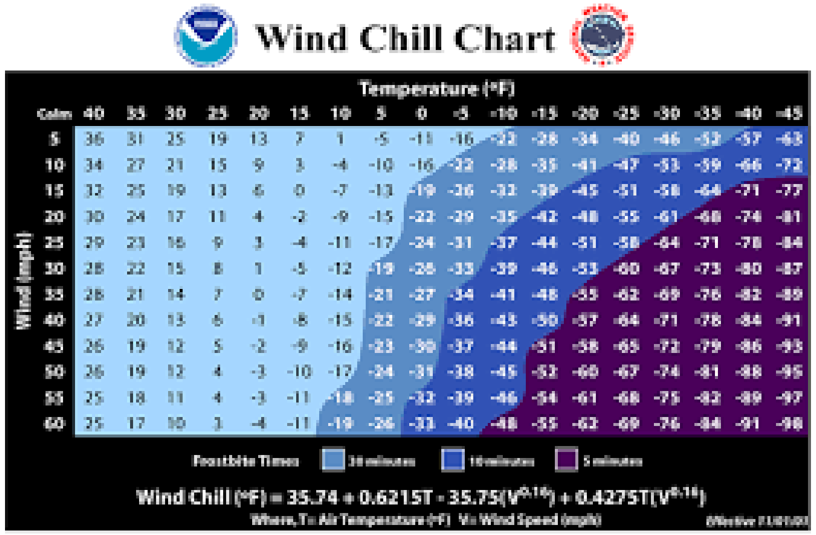
Background

- Frostbite and cold injury risk in below freezing ambient temperatures is accelerated by wind.
- National Weather Service (NWS) Wind Chill Temperature Index (WCTI) calculates skin temperatures for frostbite risk on the cheek with minimal activity levels based.
- Wind chill models have also utilized numerical methods and cylindrical models in predicting frostbite risk in humans.
- Male and Female Finite Element Thermoregulatory Models (FETM) are used to predict a more accurate WCTI with a geometrically and anatomically correct model.



Multi-layer Cylindrical Model



Wind Chill Chart

Wind (mph)	Calm 40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

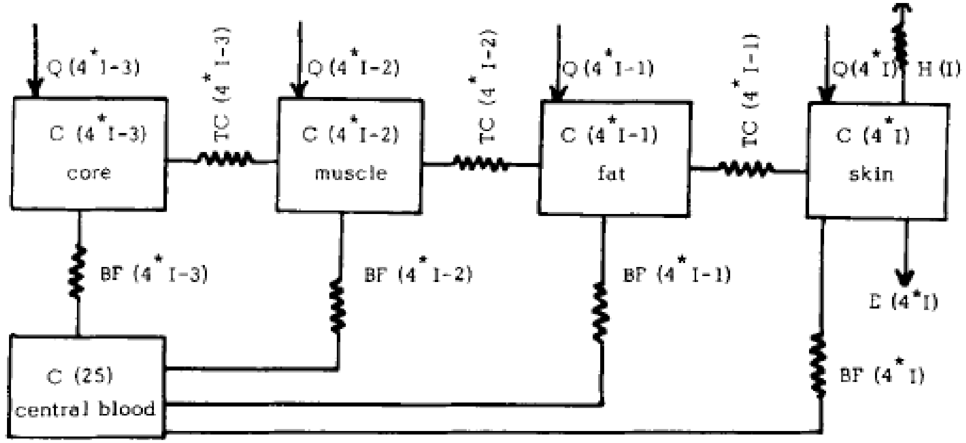
Temperature (°F)

Frostbite Times: 30 minutes, 10 minutes, 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T = Air Temperature (°F) V = Wind Speed (mph)

National Weather Service, 2001



Schematic of heat-exchange for multi-layer compartments (Stolwijk and Hardy)

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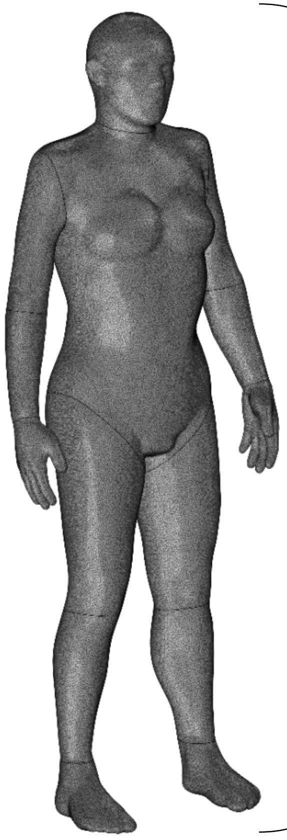
Meshing

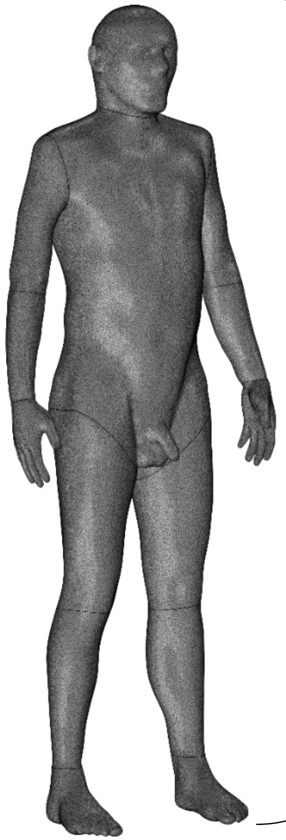
Female Mesh



36 years old
1.62 m tall
66 kg
30% Body Fat

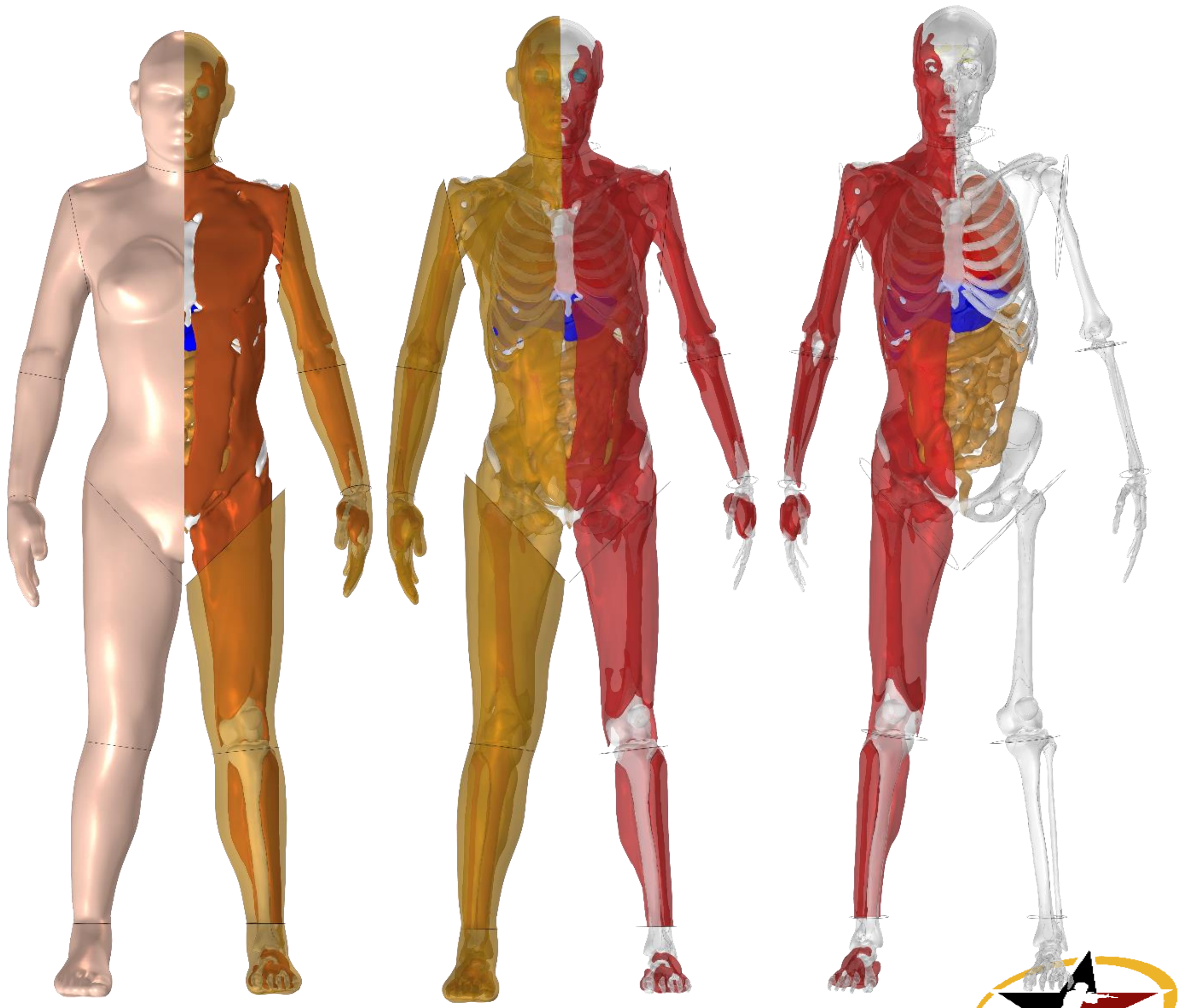
Median U.S. Female

Male Mesh



37 years old
1.76 m tall
81 kg
22% Body Fat

Median U.S. Male



Female Model Slices – Skin/Fat , Fat/Muscle, Muscle/Bones and Organs

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Passive System

COMSOL Bioheat Transfer Module

- Bio-heat Transfer Equation: $\rho C_p \frac{\partial T}{\partial t} = \lambda \nabla^2 T + Q_0 + Q_{SH} + Q_{EX} + \beta\omega\rho_b C_{p,b}(T_b - T)$

  ω → Blood flow rate

- Boundary is skin surface: $-\lambda \frac{\partial T}{\partial n} = (h_c + h_r) \cdot (T_s - T_o) + E$

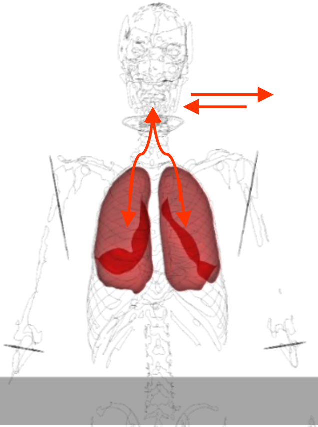
  T_o → Operative Temperature

  $T_o = \frac{T_a(h_c) + T_r(h_r)}{h_c + h_r}$

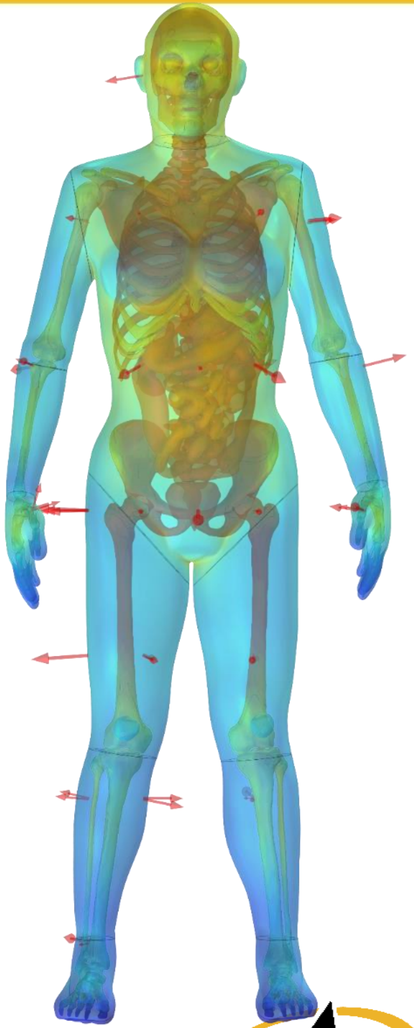
- Boundary with clothing: $-\lambda \frac{\partial T}{\partial n} = \frac{T_s - T_o}{R_{cl} + \frac{1}{f_{cl} \cdot (h_c + h_r)}} + E$

  → Clothing resistance (R_{cl}) and Dimensionless clothing area factor (f_{cl})

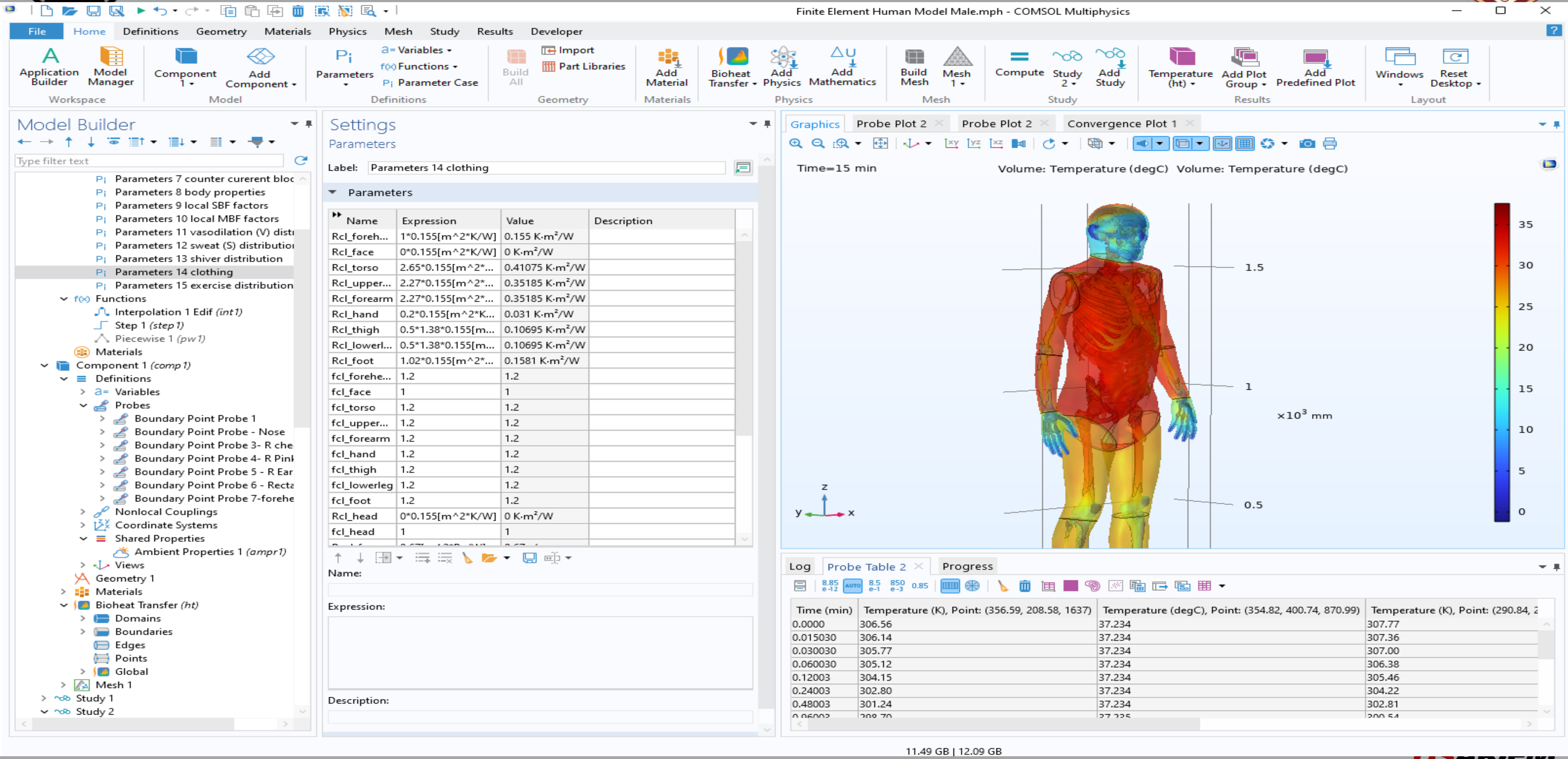
- Respiratory heat exchange: $R_{resp} = 0.0014 Q_{tot}(34.0 - T_a) + 0.0173 Q_{tot}(5.87 - 10^{-3} P_a)$



Assumption: 100% of respiratory heat exchange occurs in the lungs



Clothing



Finite Element Human Model Male.mph - COMSOL Multiphysics
File Home Definitions Geometry Materials Physics Mesh Study Results Developer
Application Builder
Model Manager
Workspace
Component 1
Add Component
Model
Parameters
Variables
Functions
Parameter Case
Definitions
Build All
Import
Part Libraries
Geometry
Add Material
Materials
Bioheat Transfer
Add Physics
Add Mathematics
Physics
Build Mesh
Mesh 1
Mesh
Compute
Study 2
Add Study
Study
Temperature (ht)
Add Plot Group
Add Predefined Plot
Results
Windows
Reset Desktop
Layout
Model Builder
Type filter text
Parameters 7 counter current bloc
Parameters 8 body properties
Parameters 9 local SBF factors
Parameters 10 local MBF factors
Parameters 11 vasodilation (V) distr
Parameters 12 sweat (S) distributio
Parameters 13 shiver distribution
Parameters 14 clothing
Parameters 15 exercise distribution
Functions
Interpolation 1 Edif (int1)
Step 1 (step1)
Piecewise 1 (pw1)
Materials
Component 1 (comp1)
Definitions
Variables
Probes
Boundary Point Probe 1
Boundary Point Probe - Nose
Boundary Point Probe 3- R che
Boundary Point Probe 4- R Pink
Boundary Point Probe 5 - R Ear
Boundary Point Probe 6 - Recta
Boundary Point Probe 7-forehe
Nonlocal Couplings
Coordinate Systems
Shared Properties
Ambient Properties 1 (ampr1)
Views
Geometry 1
Materials
Bioheat Transfer (ht)
Domains
Boundaries
Edges
Points
Global
Mesh 1
Study 1
Study 2
Settings
Parameters
Label: Parameters 14 clothing
Parameters
Name | Expression | Value | Description
Rcl_foreh... | 1*0.155[m^2*K/W] | 0.155 K·m²/W
Rcl_face | 0*0.155[m^2*K/W] | 0 K·m²/W
Rcl_torso | 2.65*0.155[m^2*... | 0.41075 K·m²/W
Rcl_upper... | 2.27*0.155[m^2*... | 0.35185 K·m²/W
Rcl_forearm | 2.27*0.155[m^2*... | 0.35185 K·m²/W
Rcl_hand | 0.2*0.155[m^2*K... | 0.031 K·m²/W
Rcl_thigh | 0.5*1.38*0.155[m... | 0.10695 K·m²/W
Rcl_lowerl... | 0.5*1.38*0.155[m... | 0.10695 K·m²/W
Rcl_foot | 1.02*0.155[m^2*... | 0.1581 K·m²/W
fcl_forehe... | 1.2 | 1.2
fcl_face | 1 | 1
fcl_torso | 1.2 | 1.2
fcl_upper... | 1.2 | 1.2
fcl_forearm | 1.2 | 1.2
fcl_hand | 1.2 | 1.2
fcl_thigh | 1.2 | 1.2
fcl_lowerleg | 1.2 | 1.2
fcl_foot | 1.2 | 1.2
Rcl_head | 0*0.155[m^2*K/W] | 0 K·m²/W
fcl_head | 1 | 1
Name:
Expression:
Description:
Graphics
Probe Plot 2
Probe Plot 2
Convergence Plot 1
Time=15 min
Volume: Temperature (degC) Volume: Temperature (degC)
1.5
1
0.5
×10³ mm
35
30
25
20
15
10
5
0
Log
Probe Table 2
Progress
Time (min) | Temperature (K), Point: (356.59, 208.58, 1637) | Temperature (degC), Point: (354.82, 400.74, 870.99) | Temperature (K), Point: (290.84, 2
0.0000 | 306.56 | 37.234 | 307.77
0.015030 | 306.14 | 37.234 | 307.36
0.030030 | 305.77 | 37.234 | 307.00
0.060030 | 305.12 | 37.234 | 306.38
0.12003 | 304.15 | 37.234 | 305.46
0.24003 | 302.80 | 37.234 | 304.22
0.48003 | 301.24 | 37.234 | 302.81
11.49 GB | 12.09 GB

Global Equation- Blood Temperature

Assumptions:

1. Temperature of venous blood exiting the tissues reached equilibrium with surrounding tissues and therefore, venous temperature is equal to tissue temperature.
2. The variation of the arterial blood temperature was considered through the countercurrent heat exchange factor (β).
3. The body has a central blood pool and temperature is independent of location.

Assumed central blood pool: $V_b \rho_b C_{p,b} \frac{dT_b}{dt} = \int \beta \omega \rho_b C_{p,b} (T - T_b) dV$

Blood temperature: $V_b \frac{dT_b}{dt} = \int \beta \omega \, (T - T_b) dV$

Active System

Name	Expression	Unit	Description
error_brain	avgBrain(T)-withsol('sol1',avgBrain(T))	K	change in brain temperat
error_skin	avgSkin(T)-withsol('sol1',avgSkin(T))	K	change in surface skin te.
warm_skin	error_skin*(error_skin>0)	K	
cold_skin	-error_skin*(error_skin<0)	K	
error	error_brain	K	
warm	error*(error>0)	K	
cold	-error*(error<0)	K	
error_heart	0[K]	K	change in heart temperat
error_body	0[K]	K	change in body temperat
T_local	0[K]	K	
val_sbf	1*cold[1/K]+1*warm[1/K]+1*cold_skin[1/K]+1*warm_skin[1/K]+1*d(avgBrain(T),t)[s/K]*(d(avgBrain(T),t)>0)+1*d(avgBrain(T),t)[s/K]*(d(avgBrain(T),t...		
T_rect	intIntestine(T*(z<0.94[m]))/intIntestine((z<0.94[m]))	K	average rectal temperatur

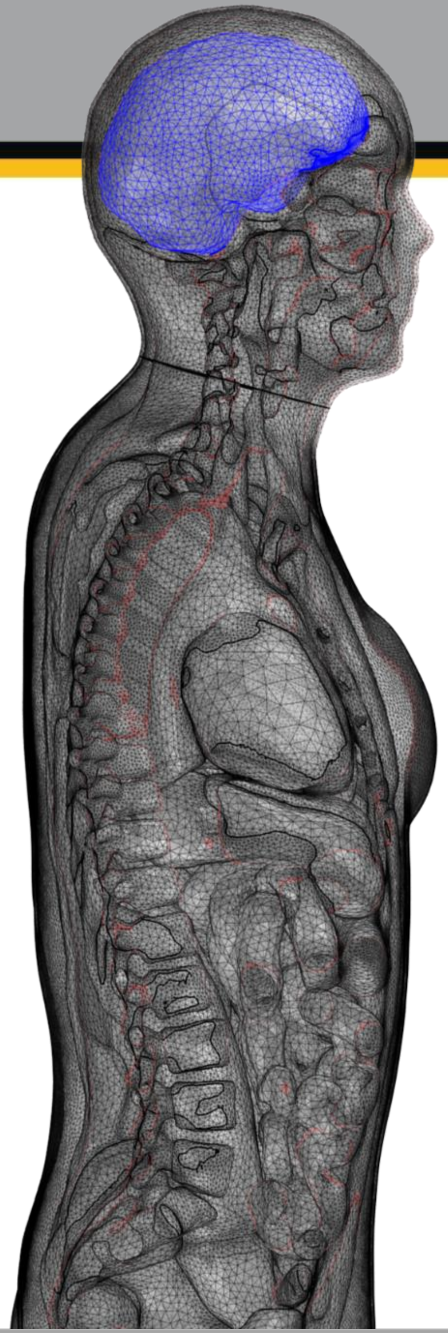
Name:

val_sbf

Expression:

1*cold[1/K]+1*warm[1/K]+1*cold_skin[1/K]+1*warm_skin[1/K]+1*d(avgBrain(T),t)[s/K]*(d(avgBrain(T),t)>0)+1*d(avgBrain(T),t)[s/K]*(d(avgBrain(T),t)<0)+1*d(avgSkin(T),t)[s/K]*(d(avgSkin(T),t)>0)
+1*d(avgSkin(T),t)[s/K]*(d(avgSkin(T),t)<0)

- Error signals in hypothalamus: $e_{hy} = T_{hy} - T_{hy_0}$
- Error signals on skin surface: $e_s = T_{ms} - T_{ms_0}$
- Vasodilation: $DI = 28424 \cdot e_{hy} + 4870 \cdot e_s$
- Vasoconstriction: $CS = 1.1 \cdot (-e_{hy}) + 3.3 \cdot (e_s)$
- Total Shivering heat production: $Q_{SH_{tot}} = \frac{147.7(-e_{hy})+44.6(-e_{ms})-1.48(e_{ms})^2}{\sqrt{PBF}}(BSA)$
- Total metabolic rate: $Q_{tot} = \int Q_0 dV + Q_{SH} + Q_{EX}$



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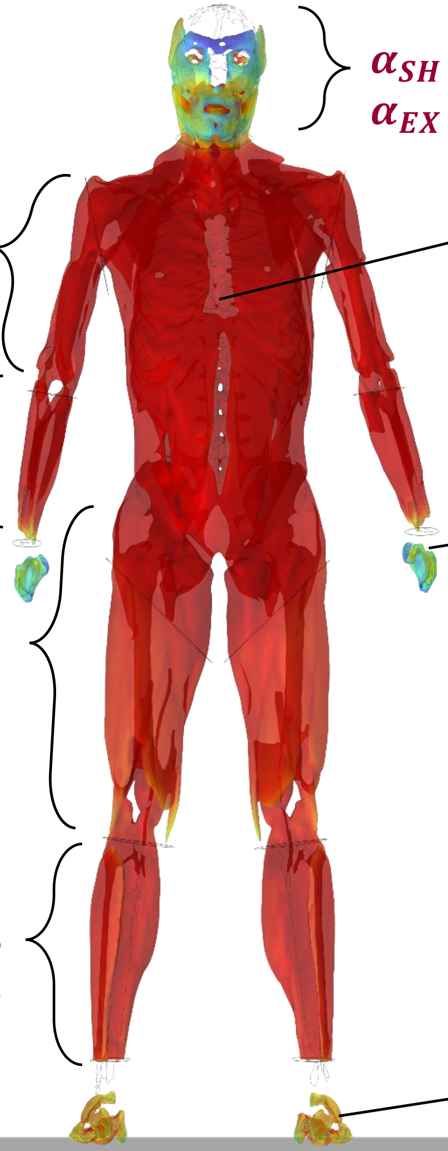
Metabolic Heat Production

$$\omega_m = \omega_{m0} + c_m \cdot (Q_{SH} + Q_{EX})$$

$$Q_{SH} = \frac{\alpha_{SH} \cdot Q_{SH,tot}}{V_i}$$

$$Q_{EX} = \frac{\alpha_{EX} \cdot Q_{EX,tot}}{V_i}$$



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Time-dependent Simulations

- **Model Validations**
  - Gavhed et. al study #1
    - 8 males preconditioned in -5℃ for 60 minutes, immediately followed by 30 minutes exposed to -10℃ with 5.0 m/s wind
  - Gavhed et. al study #2
    - Effect of moderate to high metabolic rates on thermal responses at -10℃ and 5.0m/s wind with winter clothing worn following preconditioning (2.2 Clo).
- **WCTI Simulation**
  - Auxiliary Sweep: 2.5 hours for each combination of conditions.
  - Ambient temperature between 1.7℃ (35 °F) and -42℃ (-45°F).
  - Wind speeds from 5 m/s (11.18 mph) to 20 m/s (44.8 mph) to compare results to the current National Weather Service WCTI.
  - Exposure time to skin temperature of -4.8°C.
  - Regions of the cheek, nose, and 5th finger.
  - Metabolic power rates of 107W (basal), 357W (light exercise), and 507W (moderate/heavy exercise).

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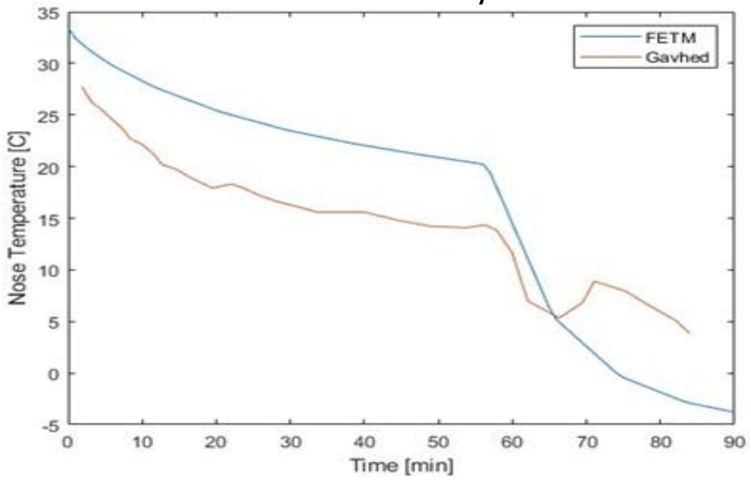
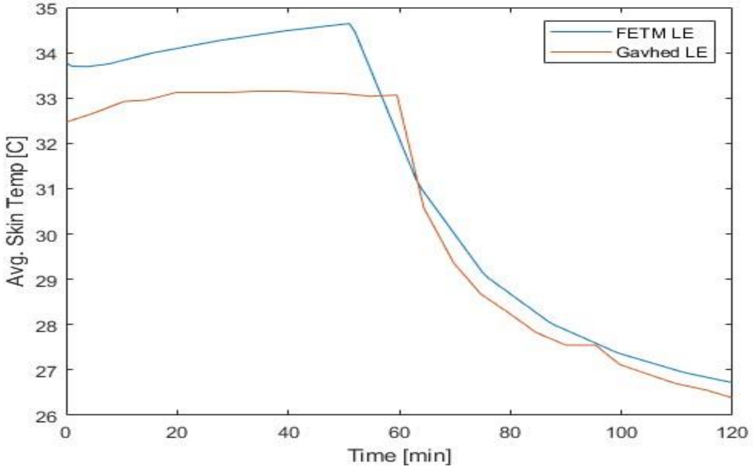
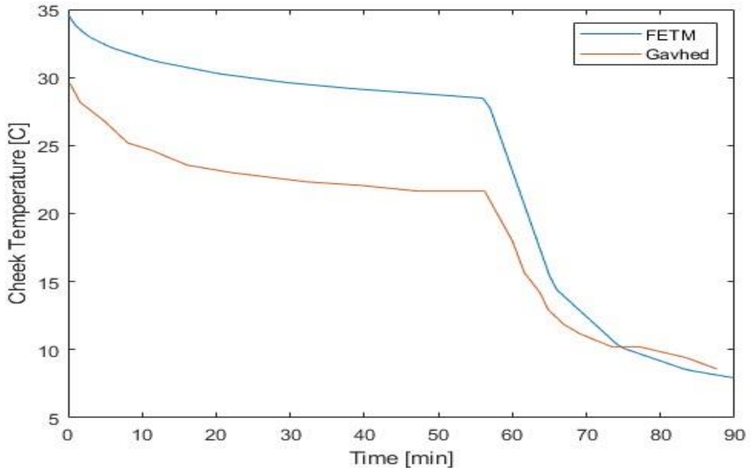
Model Validation

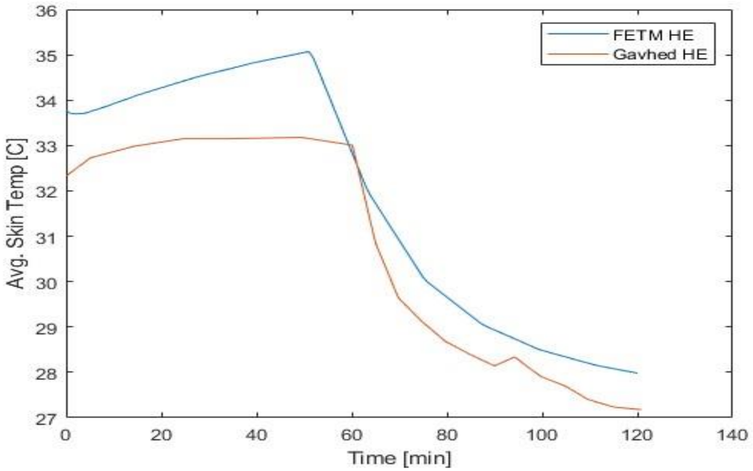
Gavhed et al study #1



Gavhed et al study #2

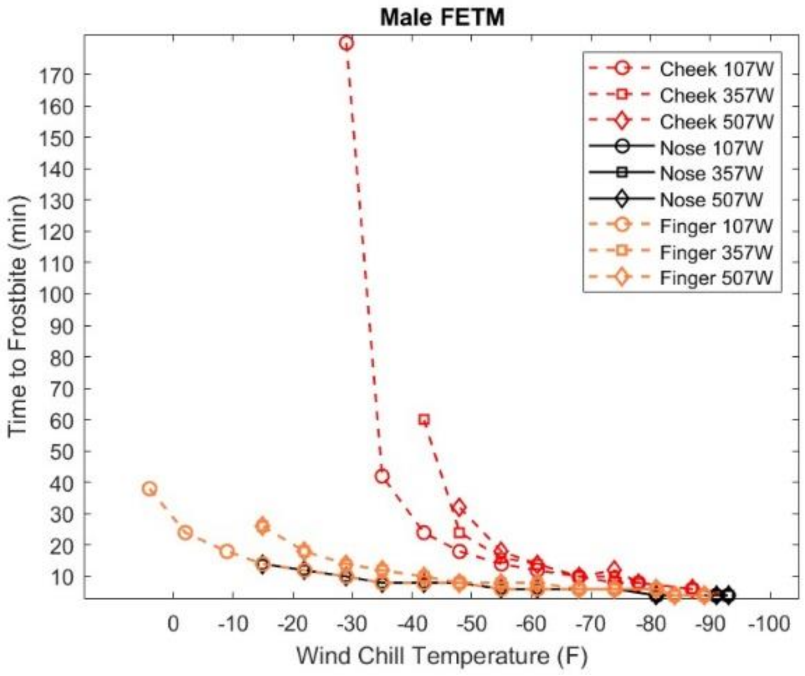


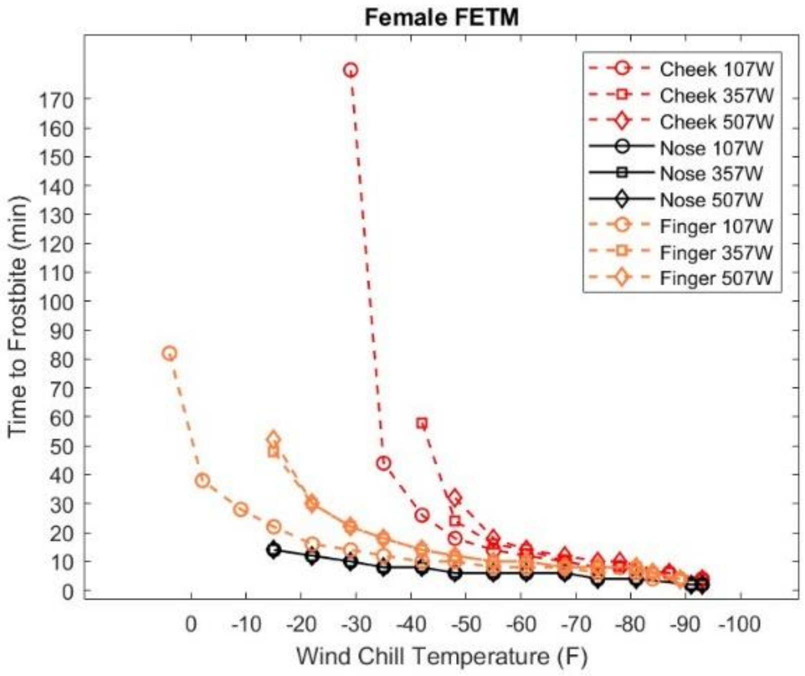


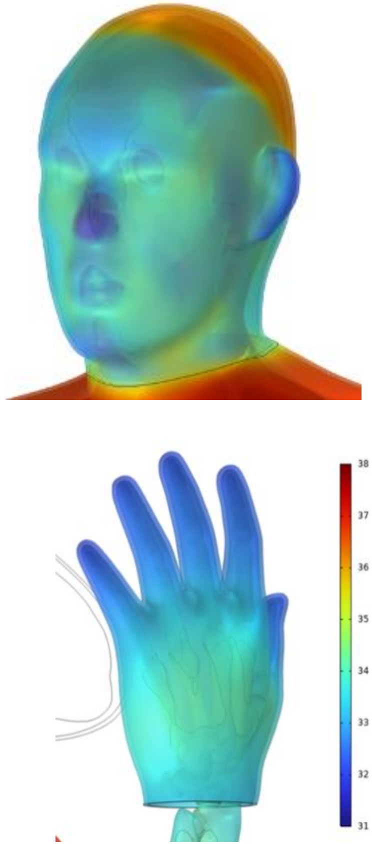


Gavhed et al study #1 vs FETM [left] for nose[top] and cheek [bottom]; Gavhed et. al study #2 [right] for average skin temperature at low intensity exercise (LE) [top] and high intensity exercise (HE) [bottom].

WCTI Simulation Results



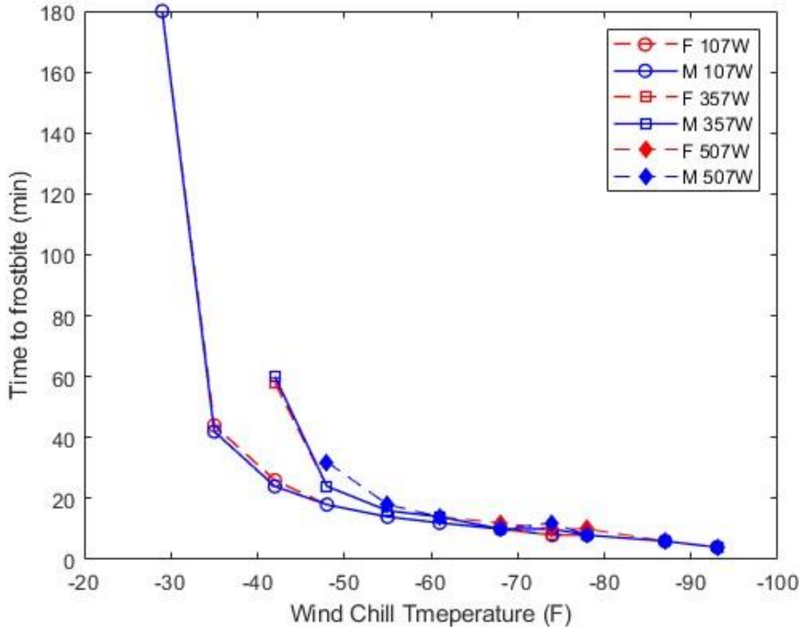




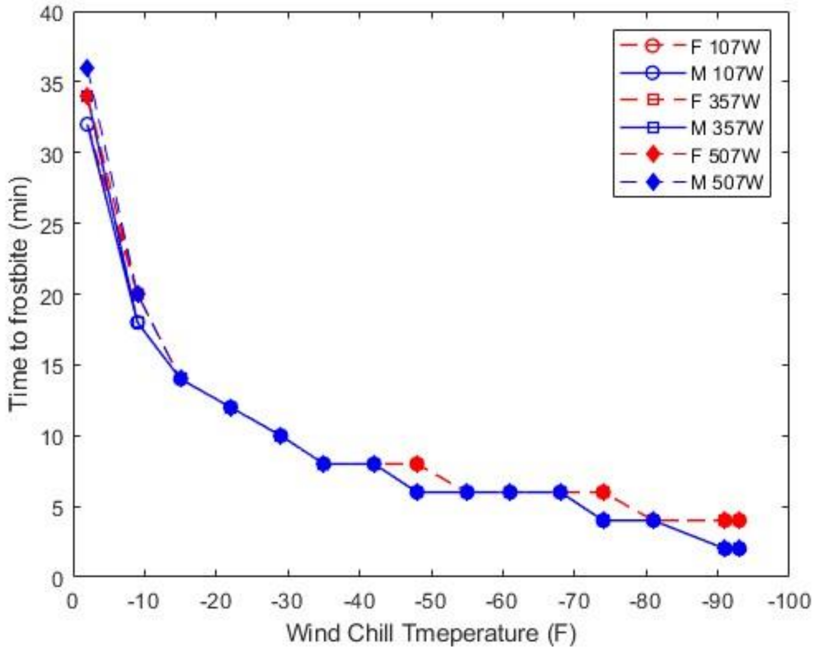
Female FETM face [top] and hand [bottom] during 0W exercise WCTI simulation.

Male vs. Female FETM

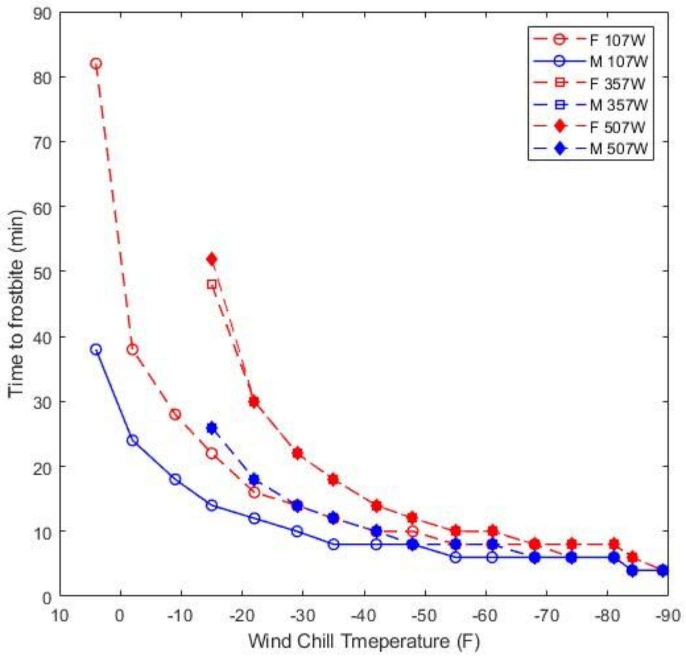
Cheek



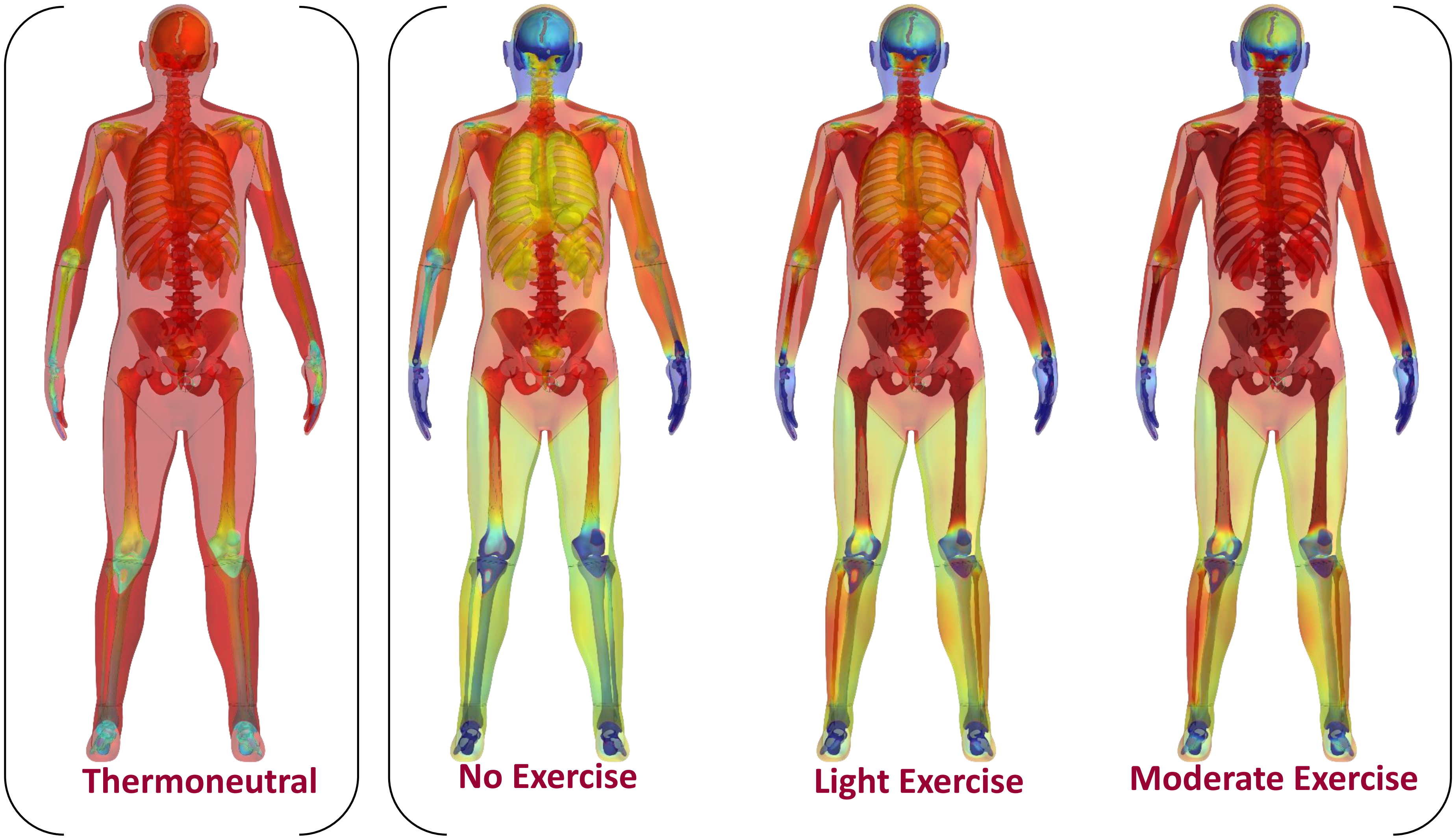
Nose



Finger



Effects of Exercise on Temperature Distribution



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Conclusion

The FETM in COMSOL Multiphysics can be used to estimate human heat transfer and thermoregulation in extreme cold and windy conditions.

The FETM simulation suggests the **nose and finger are more susceptible** to frostbite than the cheek in varied conditions and exercise can increase time to frostbite in higher wind chill temperatures (WCT).

More human studies must be conducted to validate the FETM in these conditions.

Male and female model regional skin temperatures are similar with distinct differences only recognized in the finger.

Exercise has greater impact on the cheek in higher WCT, though has a negligible effect with decreasing WCT.

Predict future individual outcomes with FETM simulation.

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2. Castellani, M.P., Rioux, T.P.; Castellani, J.W.; Potter, A.W.; Notley, S.R.; Xu, X; *A geometrically accurate 3-dimensional model of human thermoregulation for transient cold and hot environments.* Comput Biol Med, 2021. **138**: p. 104892.
3. Gavhed, D.; Makinen, T.; Holmer, I; Rintamaki, H.; *Face cooling by wind in walking subjects.* J Biometeorol, 2003. **47**: p. 7.
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