THERMO
ANALYTICS

A Thermo-physiological and Anthropometric Description of a 50th Percentile Western Female

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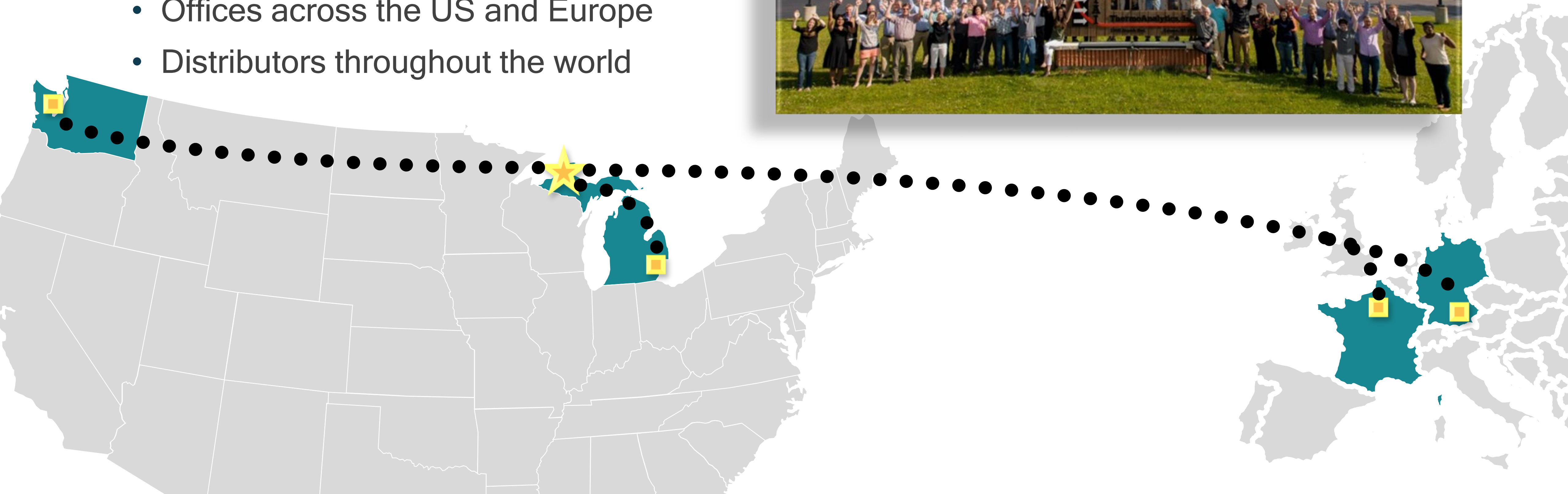
Chief Technology Officer (CTO)

THERMO ANALYTICS

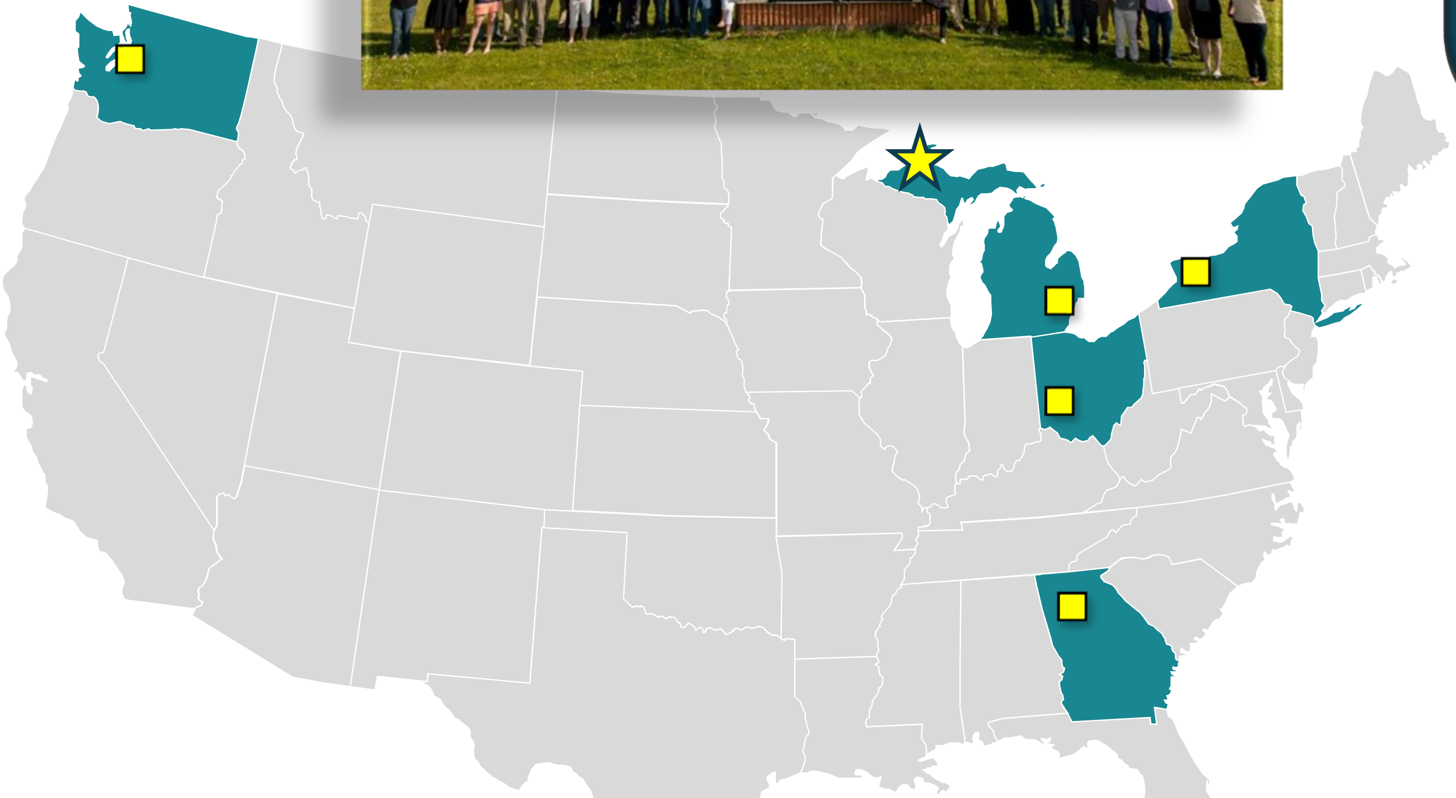
ThermoAnalytics Inc.

<u>Company background</u>

- Founded in 1996
- ESOP in 2002
- Offices across the US and Europe
- Distributors throughout the world

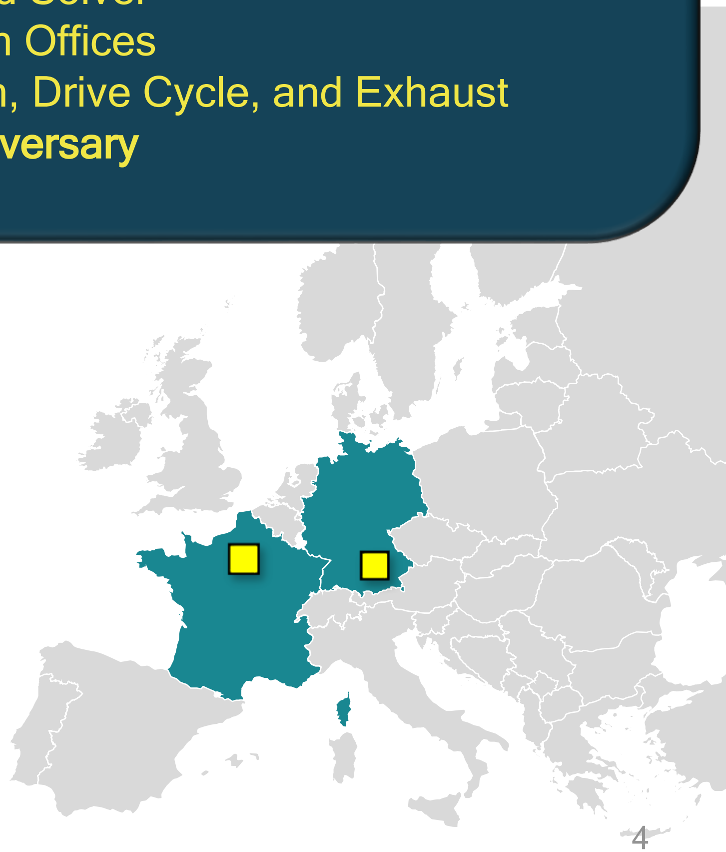


Locations & History



ThermoAnalytics History

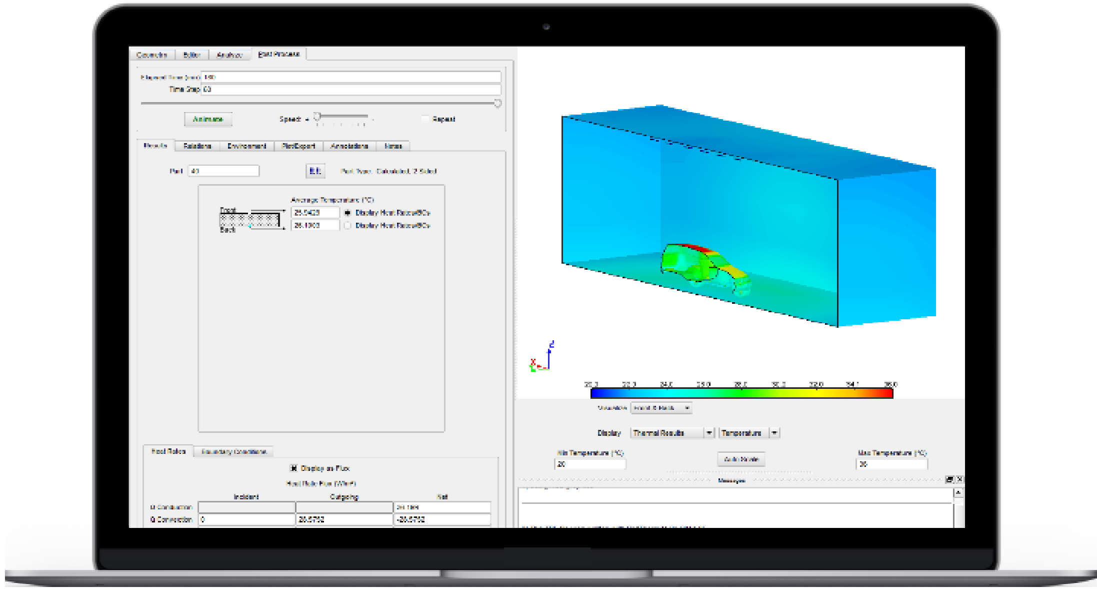
1988 Co-founder’s Independent Early Software
1994 Start of Thermal CAE software with Ford
1996 ThermoAnalytics Spin-Off from University
2002 Employee Ownership (ESOP) Established
2006 CAE Coupling
2009 ManikinPC
2011 Advanced Solver
2014 European Offices
2016 CoTherm, Drive Cycle, and Exhaust
2021 **25th Anniversary**



TAITherm

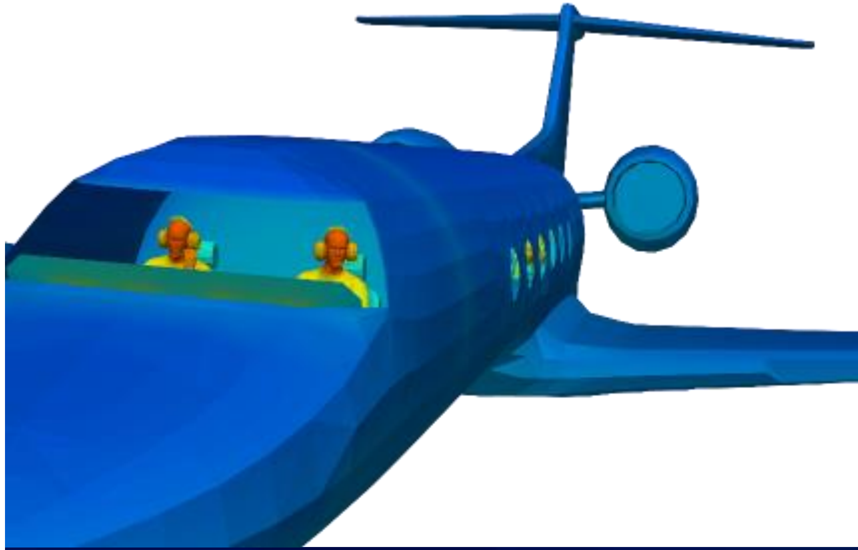
Virtual Thermal Modeling of Systems

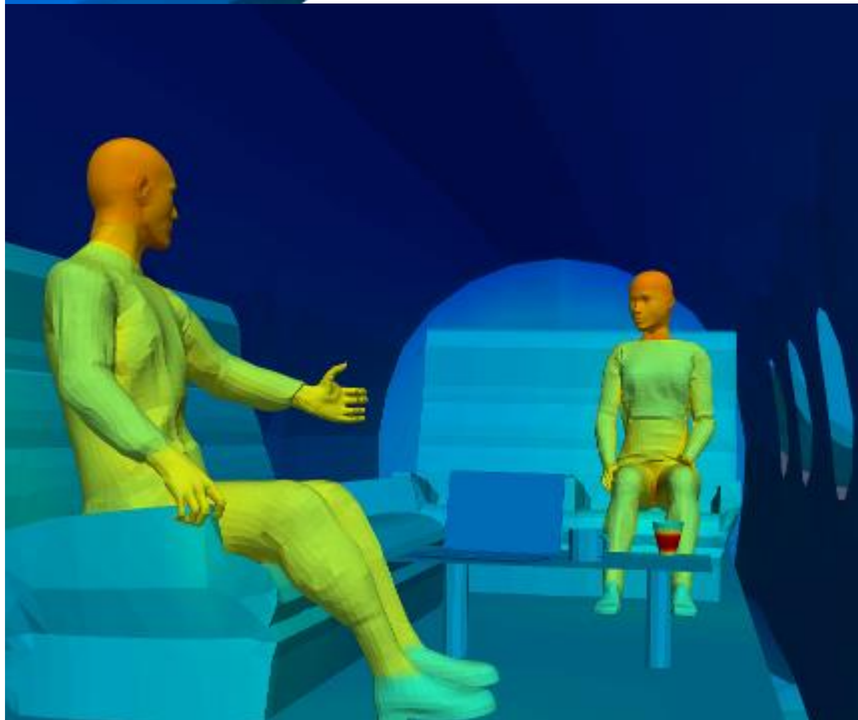
- TAITherm is a complete thermal analysis tool
  - Radiation, Conduction, Convection, Environment
  - Specialize in fast system level transient analysis
  - Laptop to High Performance Computing
- Transportation Applications
  - Vehicle Thermal Management
  - HVAC & Climate Control
  - Batteries
  - Brakes



Human Thermal

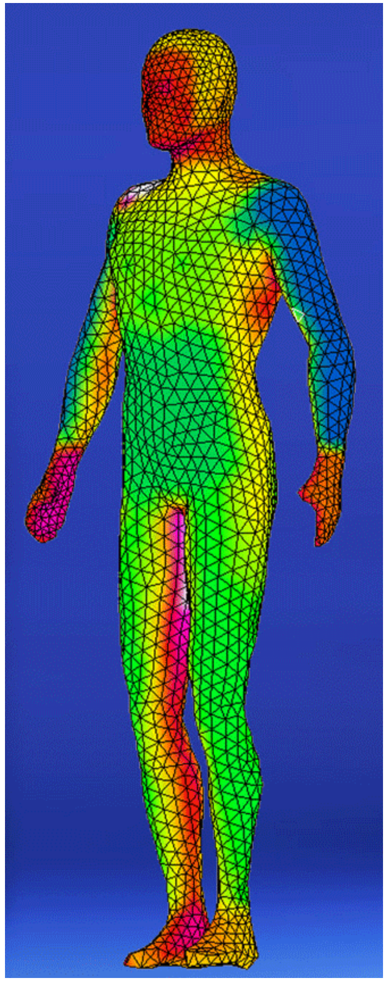
- Physiology & Thermoregulation
  - Simulate dynamic human thermal response
- Sensation & Comfort Metrics
  - Predicts localized human perception
- Manikin
  - Integrate testing & simulation
- Seat Modeling
  - Micro-climates are key to reduced energy



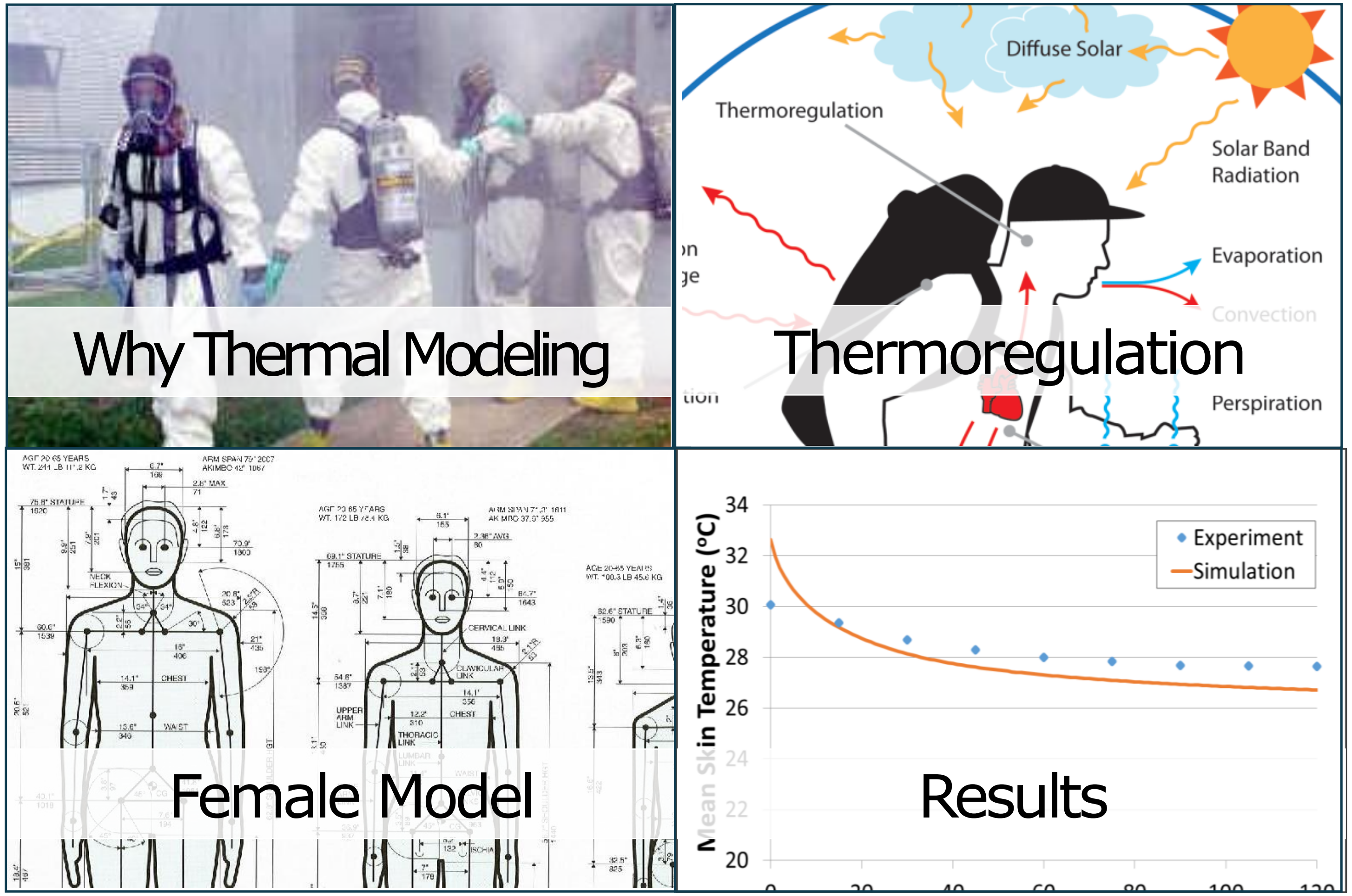


Introduction

- Thermophysiological models are used to predict thermal **sensation**, thermal **comfort** and human **effectiveness** for a wide range of environmental conditions.
- Typically, such models are based on the anthropometry and physiology of an **adult male.**
- ThermoAnalytics has developed an **adult female** model, validated against experimental results from the literature.



Agenda


Why Thermal Modeling
Diffuse Solar
Thermoregulation
Solar Band Radiation
Evaporation
Convection
Perspiration
Thermoregulation
Female Model
Mean Skin Temperature (°C)
34
32
30
28
26
24
22
20
Experiment
Simulation
Results

Human effectiveness/safety correlates to thermophysiological state

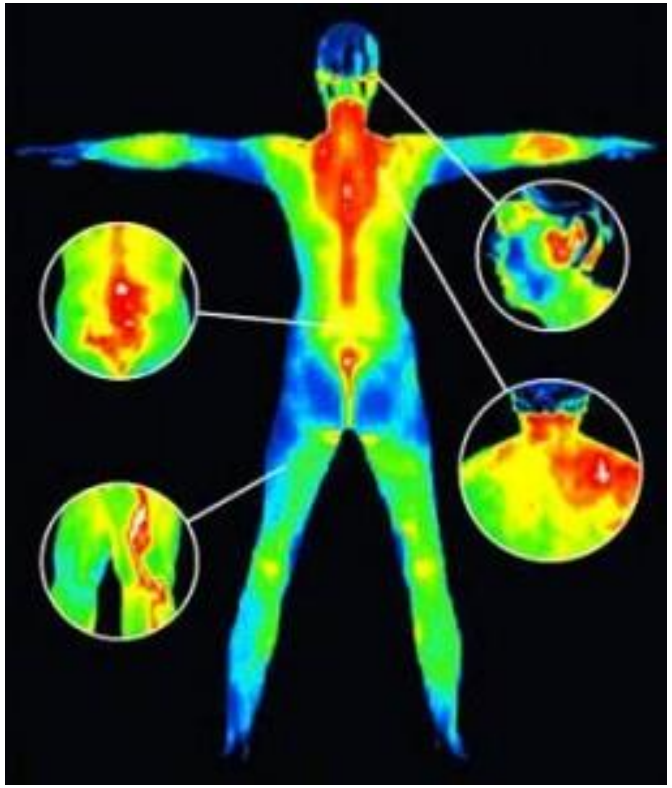
- Core temperature
- Shivering
- Sweating/dehydration
- Skin temperature/frost bite risk

Thermal comfort correlates with thermal sensation

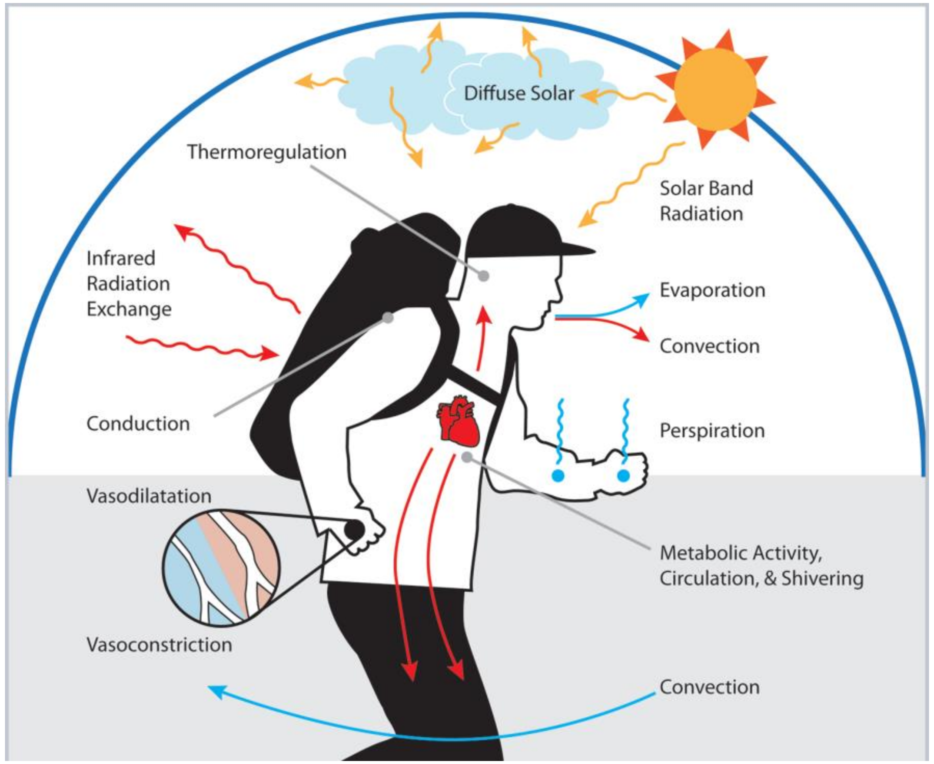
- Whole body and regional skin temperatures
- Rate of change in skin temperature
- Rate of change in core temperature

Thermography/Infrared Signature

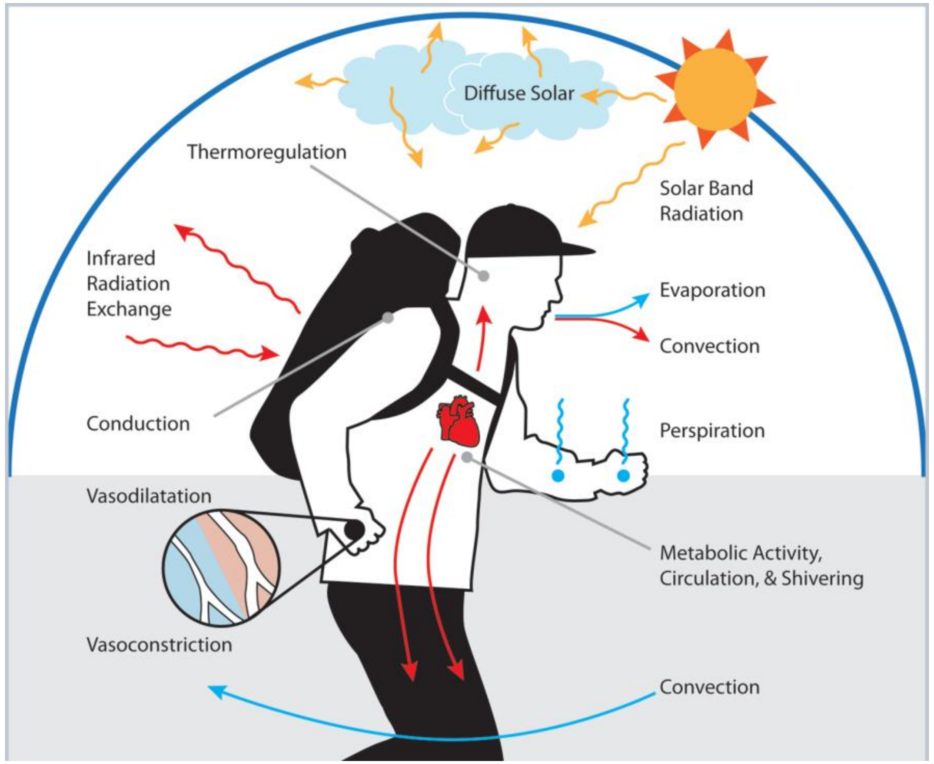
- Radiance
  - Skin temperature
  - Clothing temperature
  - Surface radiation spectral properties

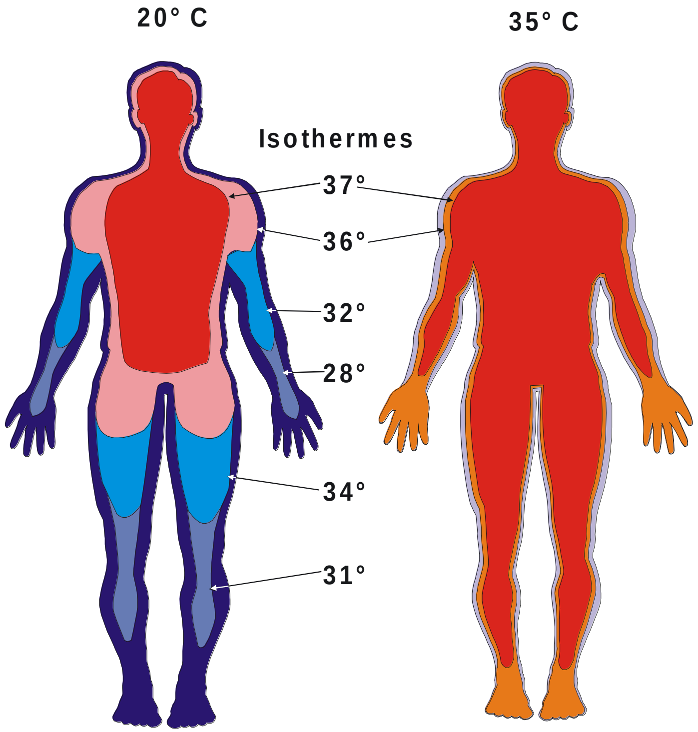


Thermoregulation: The Human Body Adjusts to its Environment



Thermoregulation: The Human Body Adjusts to its Environment



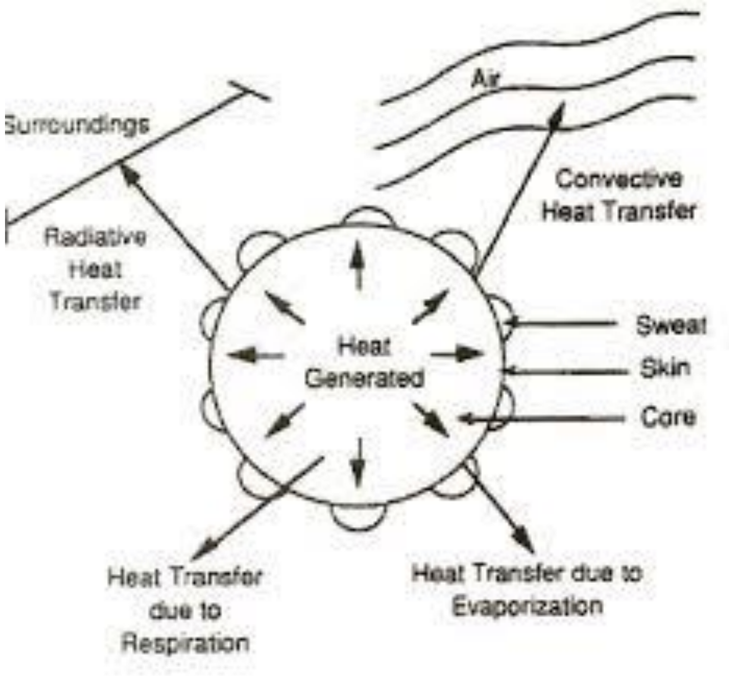


Psikuta et al (TAI UGM)

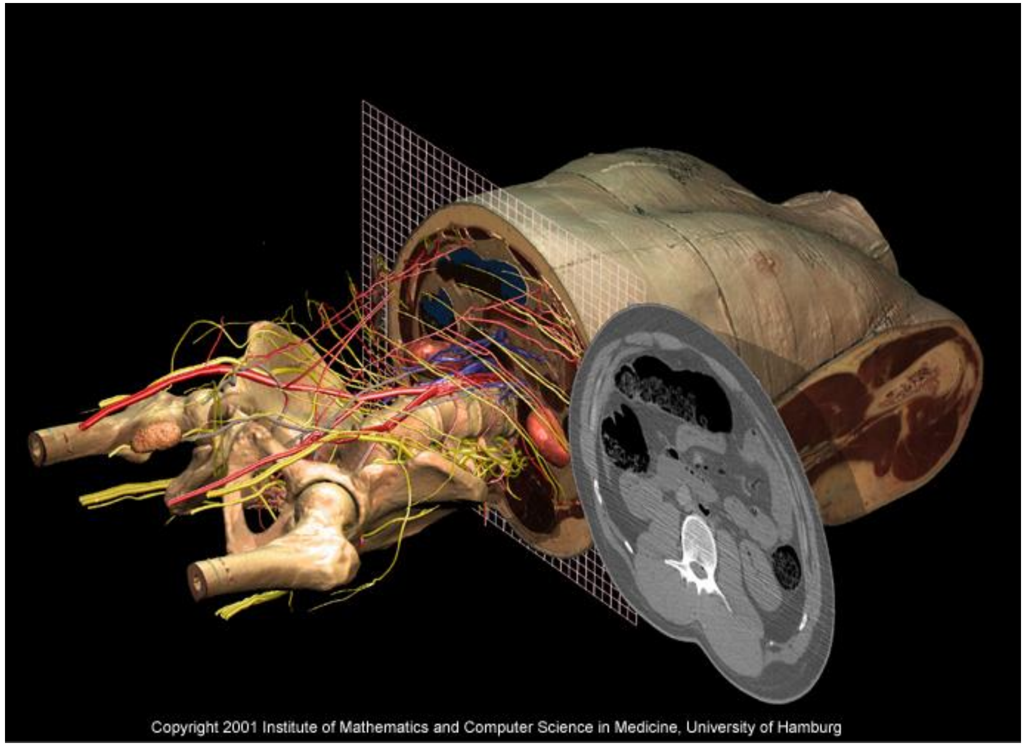

SHIVERING

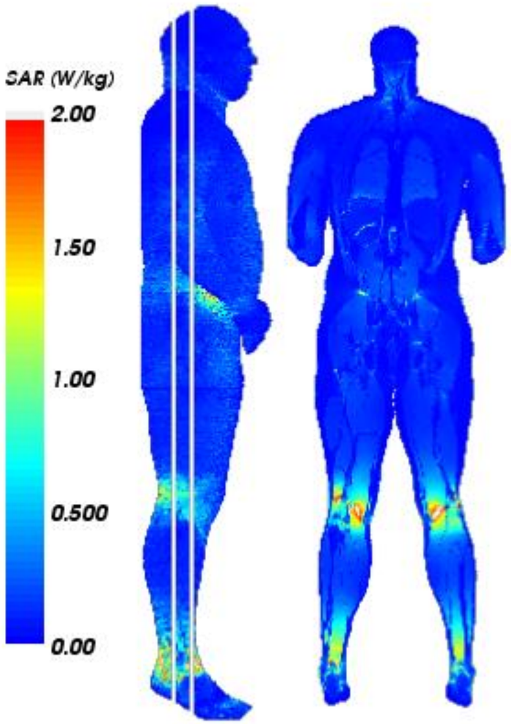

SWEATING

Basic Human Thermal Model



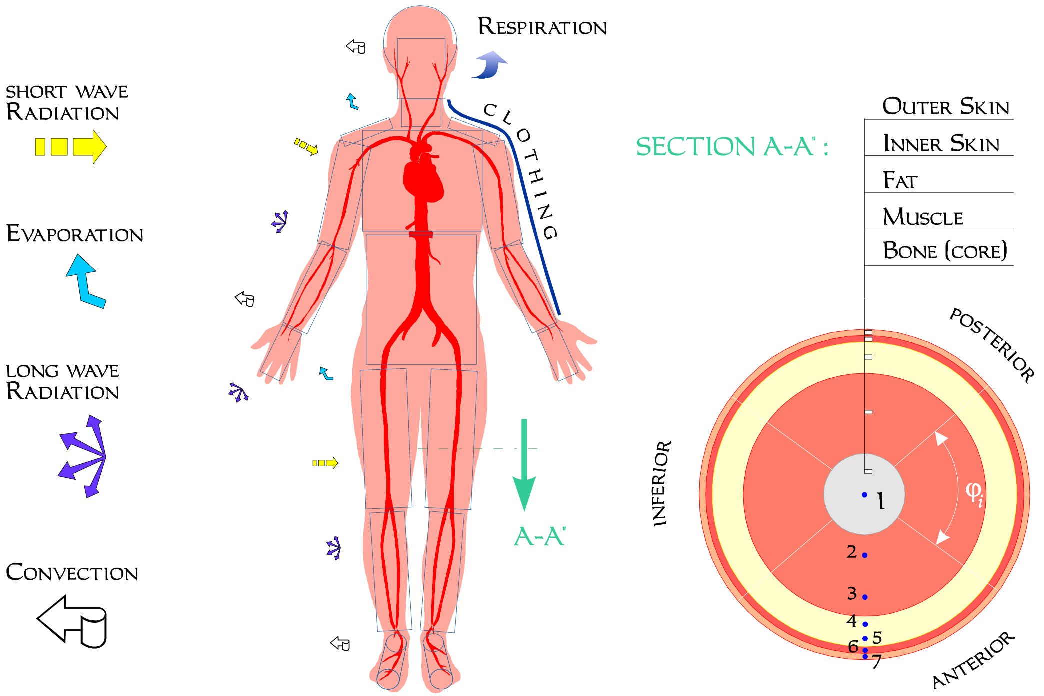
High Resolution Human Model





TAITherm Segmental Human Thermal Model

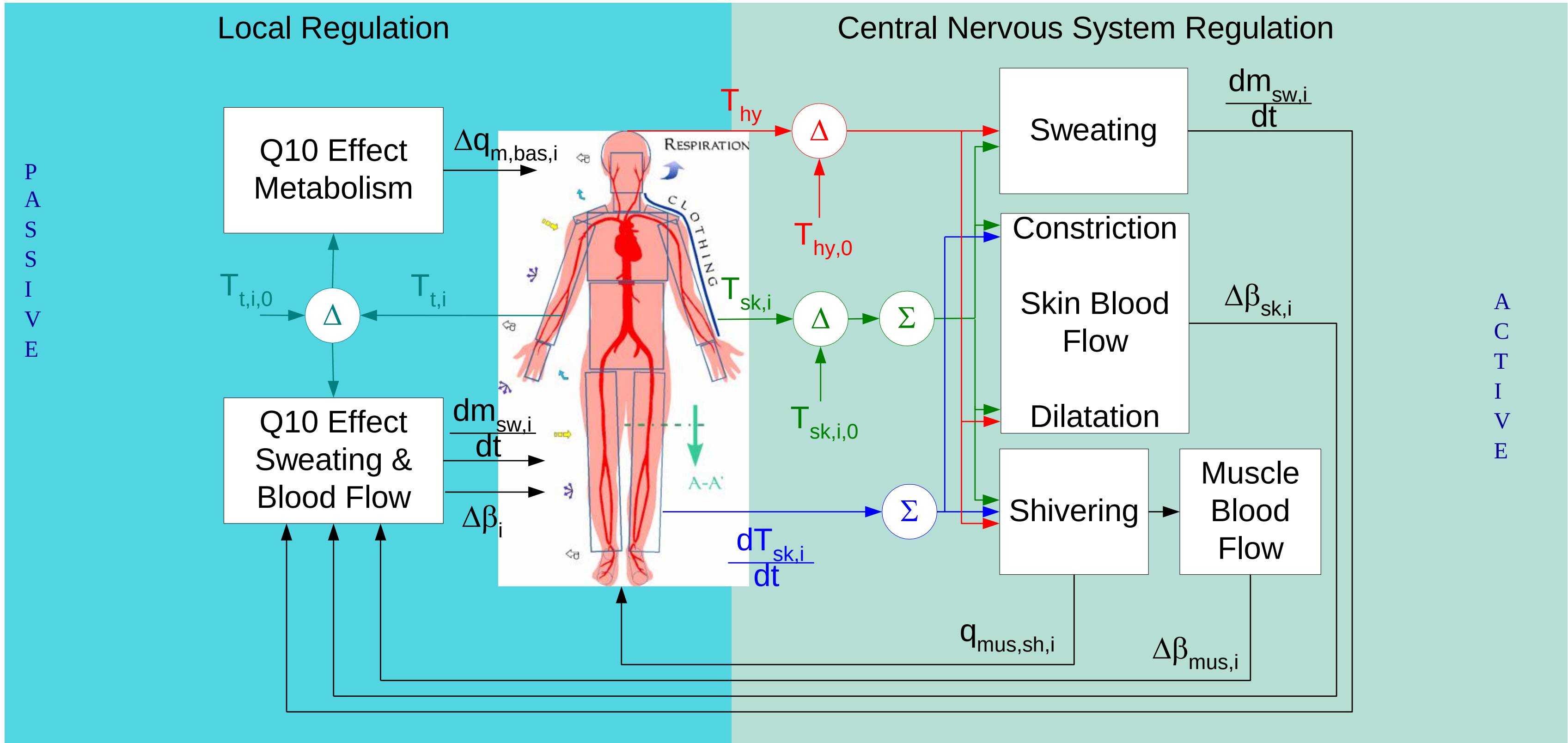
20 segment model currently in use within existing TAITherm simulation suite



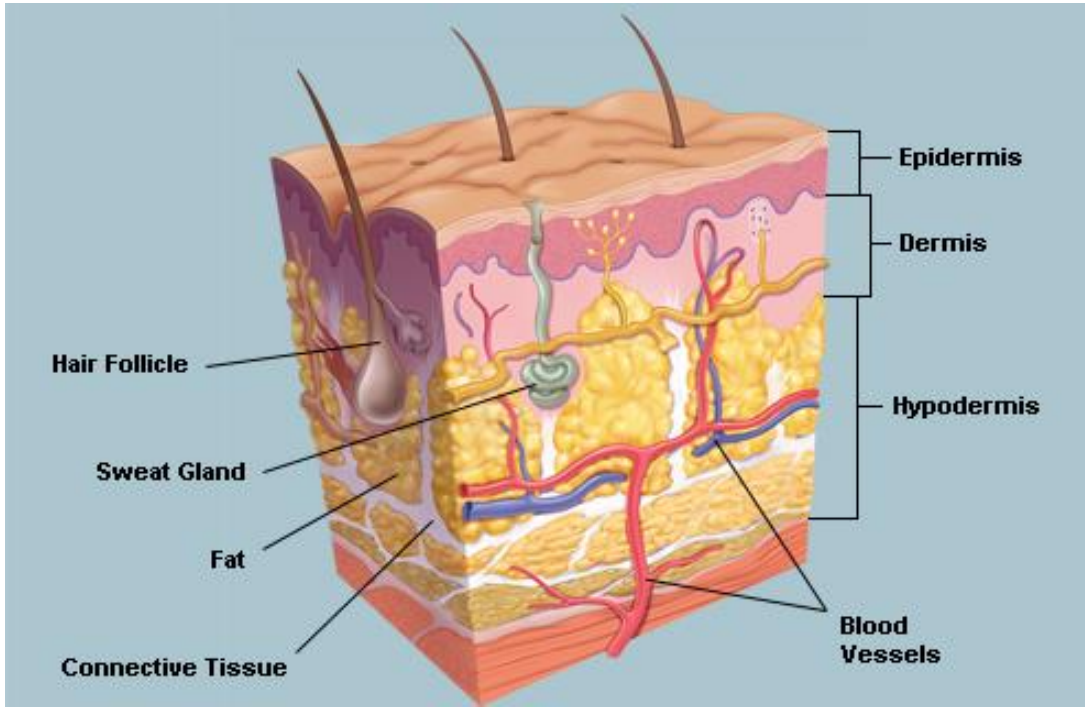
$$k_t \nabla^2 T + \dot{m}_b c_b \left(T_{art} - T\right) + \dot{q}_m + \dot{q}_{env} = \rho_t c_t \frac{\partial T}{\partial t}$$

Female Model Development Methodology

- Derive a **complete** set of system parameters
- Rely on **modern** anthropometric and thermophysiologic data in the **open literature**



Start by Defining Tissue Thermal Properties



Tissue Thermal Properties

Thermal conductivity (k)

	k (W/m-K)	ρ (kg/m^3)	c_p (J/Kg-K)	$w_{bl,0}$ (L/s/m^3)	$q_{m,0}$ (W/m^3)
Brain	0.49	1080	3850	10.132	13400
Bone	0.75	1357	1700	0	0
Fat	0.16	850	2300	0.0036	58
Skin	0.47	1085	3680	1.9	368
Muscle	0.42	1085	3768	0.538	684
Lung	0.28	550	3718	14.216	600
Viscera	0.53	1000	3697	9.55	7245

Tissue Thermal Properties

		Density (ρ)			
	k (W/m-K)	ρ (kg/m^3)	c_p (J/Kg-K)	$w_{bl,0}$ (L/s/m^3)	$q_{m,0}$ (W/m^3)
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Tissue Thermal Properties

Specific heat (c_p)

	k (W/m-K)	ρ (kg/m^3)	c_p (J/Kg-K)	$w_{bl,0}$ (L/s/m^3)	$q_{m,0}$ (W/m^3)
Brain	0.49	1080	3850	10.132	13400
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Tissue Thermal Properties

Basal blood perfusion ($w_{bl,0}$)

	k (W/m-K)	ρ (kg/m³)	c_p (J/Kg-K)	$w_{bl,0}$ (L/s/m³)	$q_{m,0}$ (W/m³)
Brain	0.49	1080	3850	10.132	13400
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Tissue Thermal Properties

Basal metabolic rate ($q_{m,0}$)

	k (W/m-K)	ρ (kg/m^3)	c_p (J/Kg-K)	$w_{bl,0}$ (L/s/m^3)	$q_{m,0}$ (W/m^3)
Brain	0.49	1080	3850	10.132	13400
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Lung	0.28	550	3718	14.216	600
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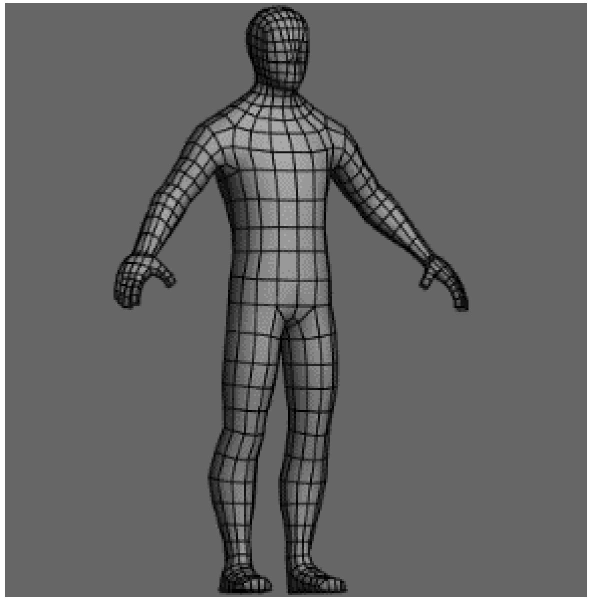
A complete scalable set of system parameters was derived from the literature

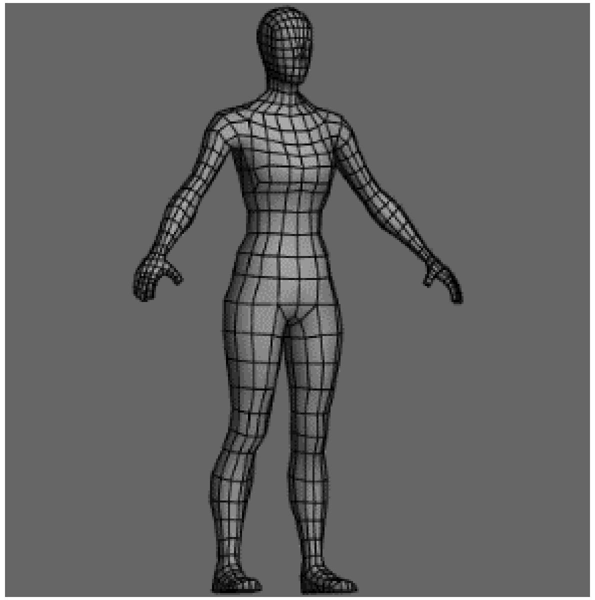
- Passive parameters
  - Height, Weight
  - Surface Area
  - Basal Metabolism
  - Basal Blood Flow
  - Cardiac Output
  - Segment Lengths and Circumferences
  - Skin, Fat, Muscle thicknesses
  - Bone Mass
- Active parameters
  - Skin Sensitivity, Distribution Coefficients
  - Sweating, Shivering
  - Vasoconstriction, Vasodilatation

Whole Body Parameters

Whole body parameters	Male value
Height	1.75 m
Weight	79.3 kg
Surface area	1.95 m^2
Basal metabolism	87.1 W
Cardiac output	5.59 L/min
Sweat, Sw (g/min), scaling factor	-
Shivering, Sh (W), scaling factor	-
Dilatation, Dl (W/K), scaling factor	-
Constriction, Cs (-), scaling factor	-

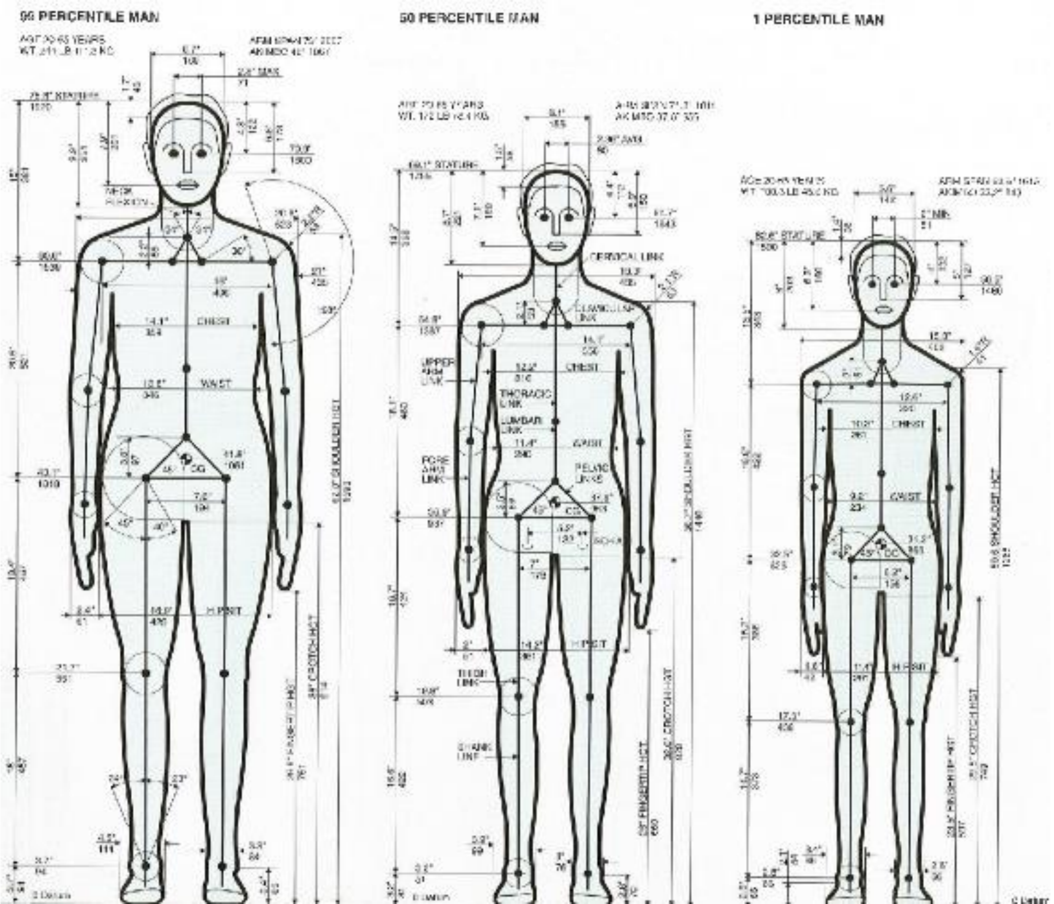


Whole body parameters	Female value
Height	1.63 m
Weight	66.6 kg
Surface area	1.71 m^2
Basal metabolism	68.8 W
Cardiac output	4.91 L/min
Sweat, Sw (g/min), scaling factor	0.6
Shivering, Sh (W), scaling factor	0.83
Dilatation, Dl (W/K), scaling factor	0.87
Constriction, Cs (-), scaling factor	0.87



Dimensional Parameters

- The Measure of Man and Woman (Dreyfus 2002)

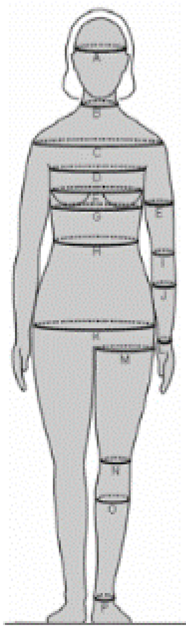


Segment-level Parameters

- Multiple anthropometric databases relied on to harmonize whole body properties with segment properties

- Wealth of research available from crash test dummy design efforts

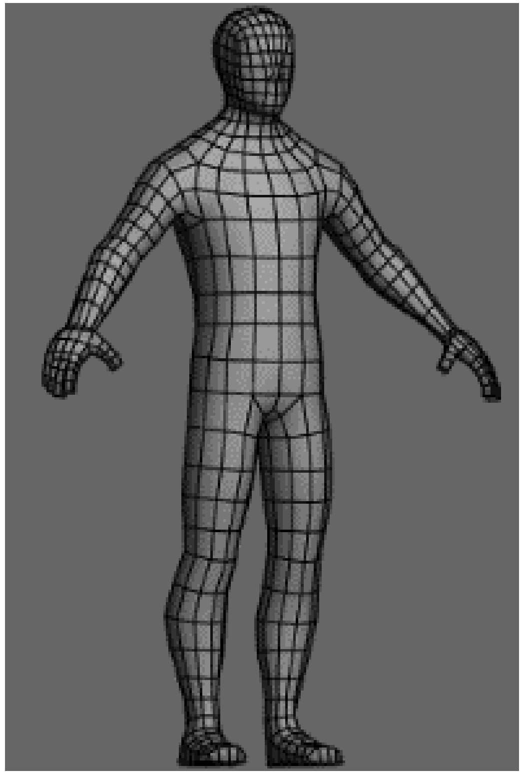
Comparison of anthropometric data (circumferences) of the 50th percentile female. Based on [44], [46], GEBOD, and RAMSIS.



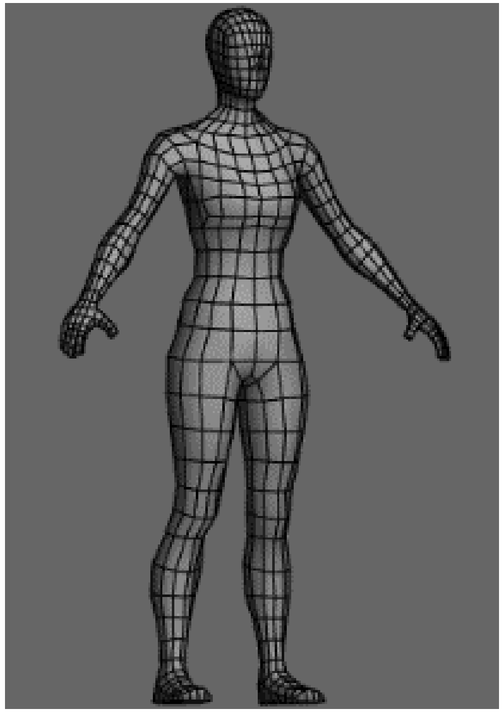
Body Part	Circumference [cm] [46]	[44]	GEBOD	RAMSIS
Stature [cm]	161.5	161.2	161.8	161.8
Mass [kg]	65.8	63.9	62.3	62.3
A Head	54.9	54.8	-	-
B Neck	35.1	32.9	34.3	-
C Shoulder	98.0	-	-	-
D Arm pit	89.2	-	-	-
E Arm[3)]	29.0[1)]	28.8[1)]	27.1	21.7
F Bust	95.8	95.4	-	-
G Chest[4)]	79.0	-	-	-
H Waist	74.2	-	-	74.6
I Elbow	28.2[1)]	24.4[2)]	27.5	-
J Forearm	26.2[1)]	21.2[2)]	24.2	23.7
K Hip	100.8	100.1	-	-
L Wrist	15.5	15.7	15.2	-
M Thigh	59.2	59.4	58.0	-
N Knee	38.1	37.0	38.5	-
O Calf	35.8	35.8	35.3	33.8
P Ankle	21.8	21.4	21.5	-

1) Flexed
2) Relaxed
3) Upper Arm
4) Below Bust
5) Upper Thigh

Passive System: Female vs Male

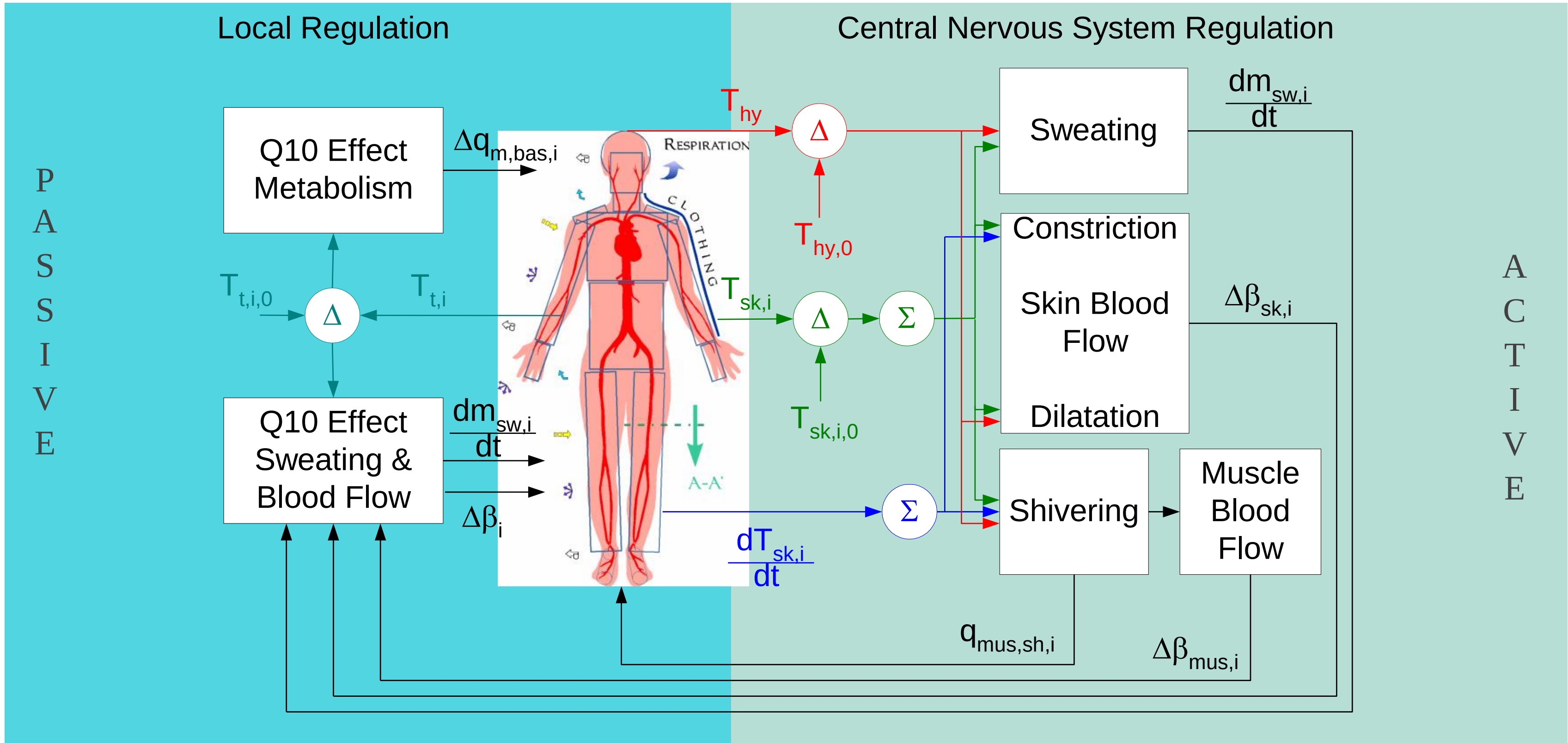


For Each Model Segment
Segment Length
Segment Circumference
Skin Thickness
Fat Thickness
Muscle Thickness
Bone Thickness



The Active System

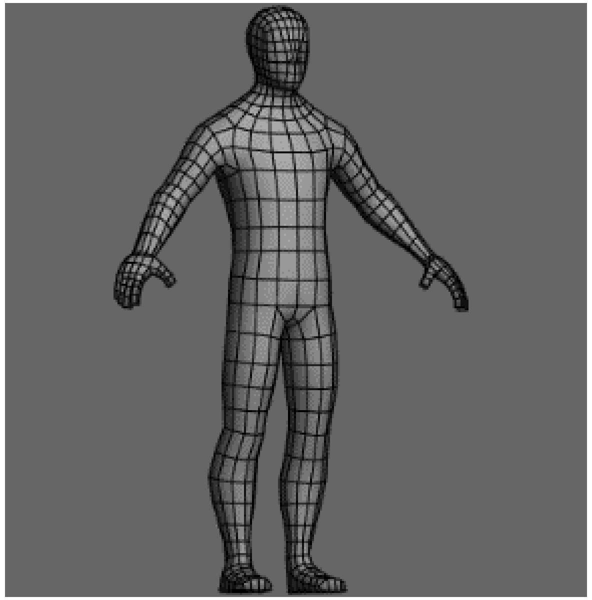
- The active system physiological parameters that characterize the central nervous system response to thermal stimuli



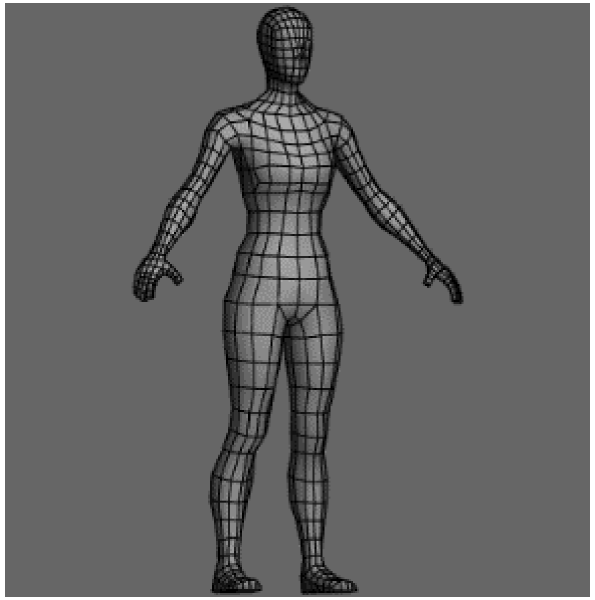
Active System: Skin Sensitivity

- Cotter and Taylor cutaneous sudomotor weightings used to facilitate skin sensitivity values
  - Process of open-loop, whole-body assessment of localized cutaneous skin response
    - Water perfusion suit clamped whole body skin and core temperatures sans the localized site where ambient temperature was varied to illicit response
  - Response values were combined with segment geometric skin area

Active System: Skin Sensitivity



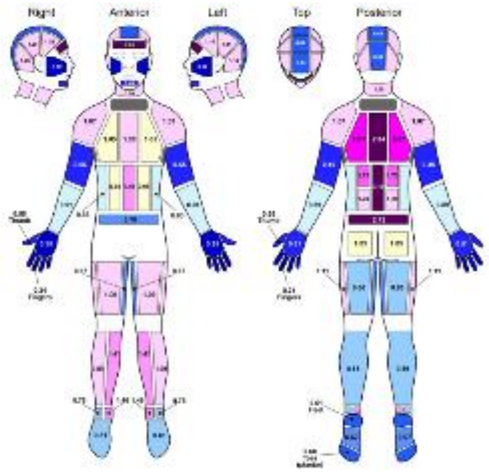
Skin Sensitivity		
Male Value (m)	Compartment	Female Value (m)
0.0835	Head	0.0473
0.0418	Face	0.0517
0.0417	Neck	0.0409
0.0150	LeftShoulder	0.0356
0.0150	RightShoulder	0.0356
0.0645	Chest	0.0800
0.0645	Back	0.2087
0.1210	Abdomen	0.1300
0.0450	LeftUpperArm	0.0350
0.0450	RightUpperArm	0.0350
0.0450	LeftLowerArm	0.0200
0.0450	RightLowerArm	0.0200
0.0450	LeftHand	0.0100
0.0450	RightHand	0.0100
0.0520	LeftThigh	0.0600
0.0520	RightThigh	0.0600
0.0520	LeftLowerLeg	0.0500
0.0520	RightLowerLeg	0.0500
0.0375	LeftFoot	0.0100
0.0375	RightFoot	0.0100



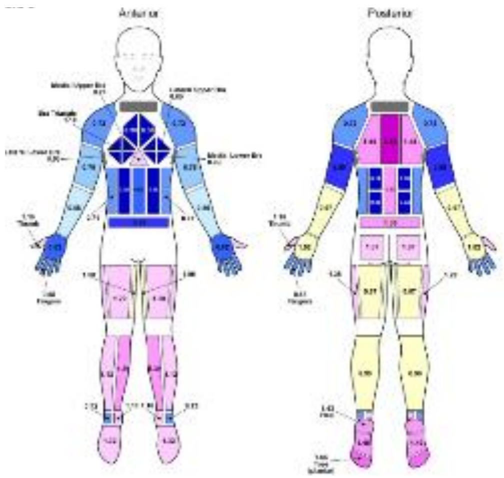
Sweat Distribution

- Sweat distribution coefficients were derived from research performed by Smith and Havenith (2011, 2012)
  - Modified absorbent technique was used to collect sweat for investigating regional sweat rates
- Sweat is distributed in females more heavily towards the lower body than for males

Male Intensity Values



Female Intensity Values



Lessons Learned – Sweat Rates

- Males have more brute-force sweat response than females
  - Remarkable sex difference was observed in the sweat rates; they were sig. higher in the men…Morimoto (1966, JAP)
  - Women generally have lower sweat rates an appropriate adjustment to lesser cooling needs…Nunneley (1978, MedSciSports)
  - Greater efficiency of temperature regulation by these females than the males cannot derive from sex differences in metabolism…Weinmann (1967, JAP)

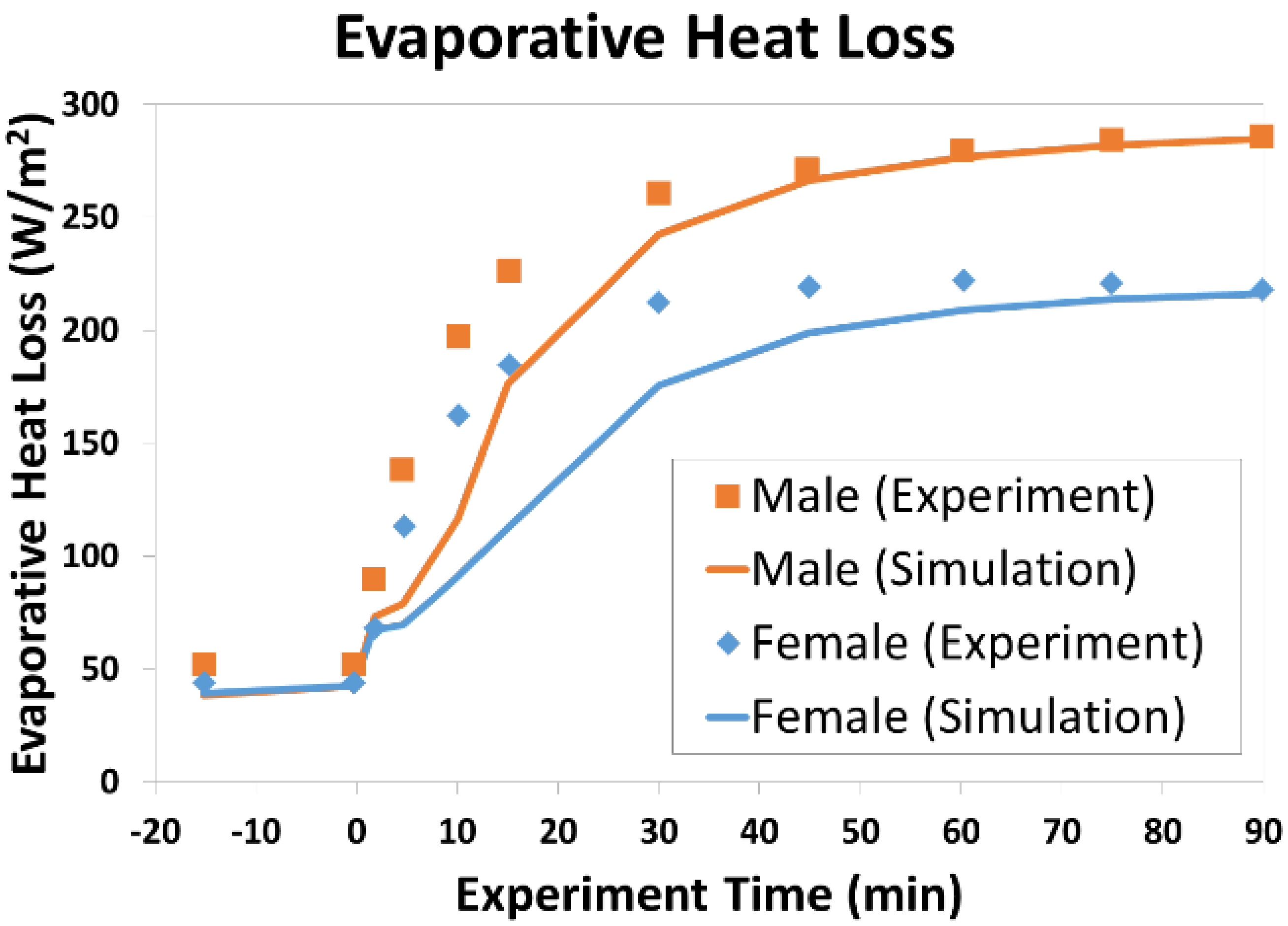
Testing the Complete Model

- The female model was tested by comparing its results (**core temperature, whole body sweat rate, skin blood flow**) to published experimental results
  - Exercise in male and female cohort groups

Gagnon, D and Kenny, G. P. *Sex Modulates Whole-Body Sudomotor Thermosensitivity during exercise*. J. Physiol 589: 6205-6217, 2011.

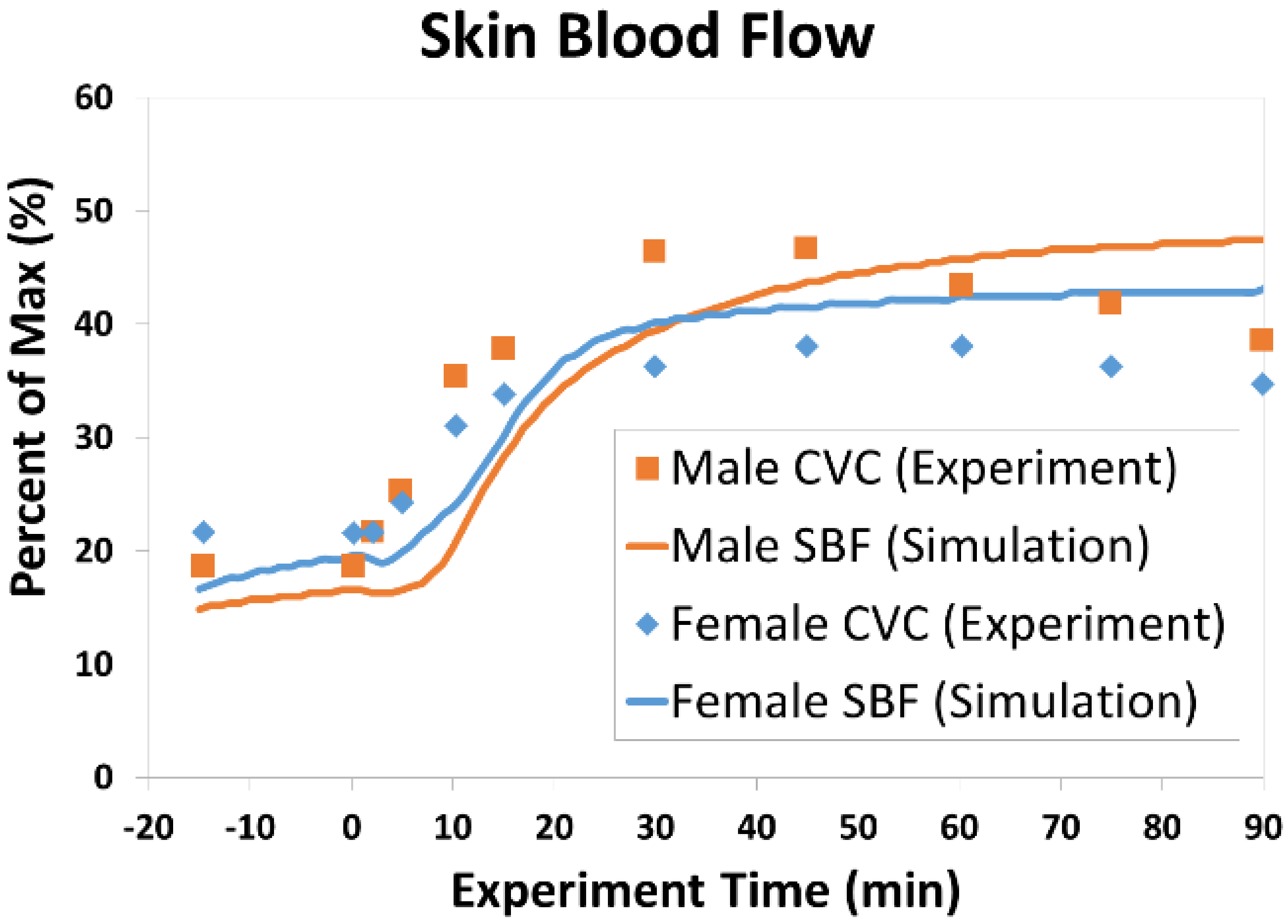
- **Predicted** and **measured** evaporative heat losses and rates of skin blood flow during exercise at 50% $VO_{2,max}$
- The rise in core (**rectal**) temperature for the female
  - $\Delta T_{re,simulation} = 1.32\ ^oC$
  - $\Delta T_{re,experiment} = 1.22^oC$

Evaporative Heat Loss Predictions



Evaporative heat loss during exercise at 50% VO_{2max}

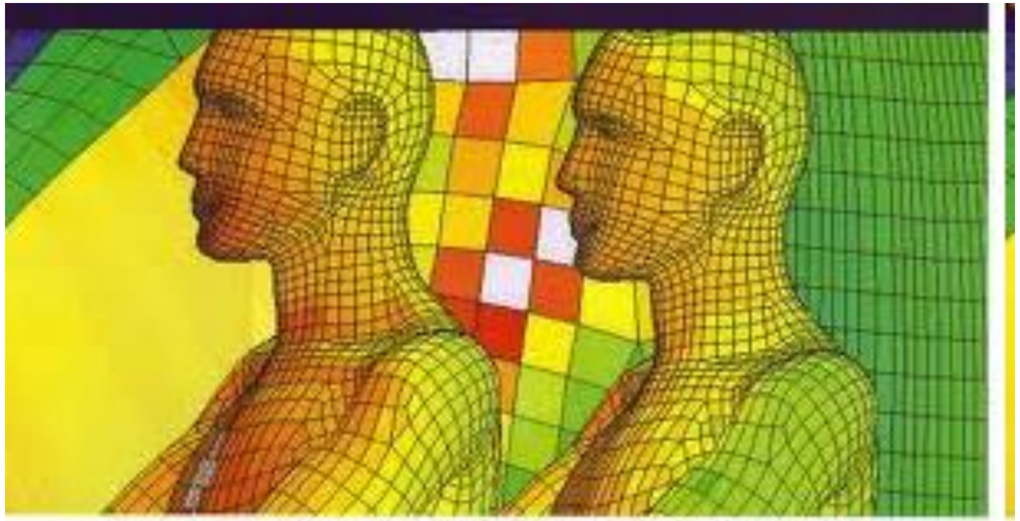
Skin Blood Flow Predictions



Skin blood flow responses during exercise at 50% VO_{2max}

Conclusion

- A **female** thermophysiology model developed from anthropometric data is **more capable** of simulating thermoregulatory response (core temperature, sweat rate and skin blood flow) in exercising women, compared with an existing model based on a **standard adult male**.



Thank you

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