Universität Rostock

Bioheat Modelling and Simulation for Body Heat Powered Medical Implants

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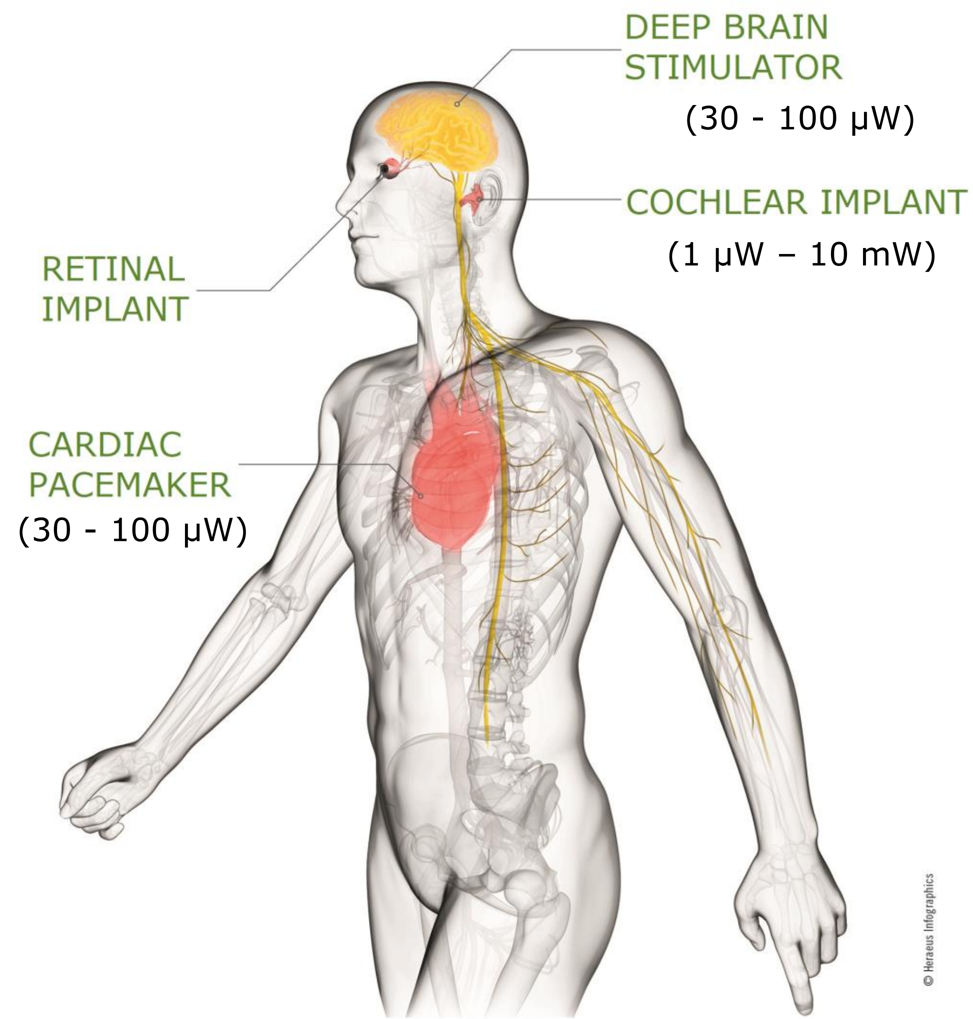
Outline

- Implants and their power needs
- State of the art
- Stationary heat transfer in humans
- Thermoregulatory control loop (Transient analysis)
- Conclusion and outlook

Implants and their power needs

- Electrically active implantable medical devices gaining interest
- Usually powered by non-rechargeable batteries
- Battery operated implants require re-intervention surgeries every 7 or 8 years for replacement

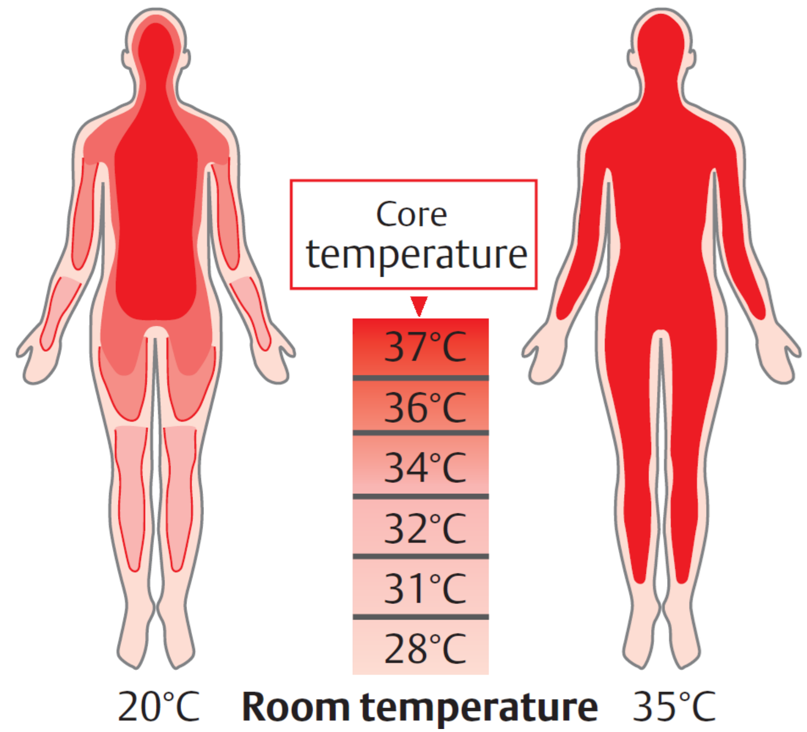


Parsonnet, V. and Cheema, A., 2003, Pacing and Clinical Electrophysiology, 26(12)
https://www.heraeus.com/media/media/group/media_group/press/2016_1/02_cermet/Cermet_Infographics_EN.jpg

Implants and their power needs

Thermoelectric energy harvesting

- Human body potential power source for the implant
- Thermal gradient between skin surface and body core (stays stable at about 37 °C)
- Thermoelectric generators (TEGs) present viable opportunity to exploit available temperature difference

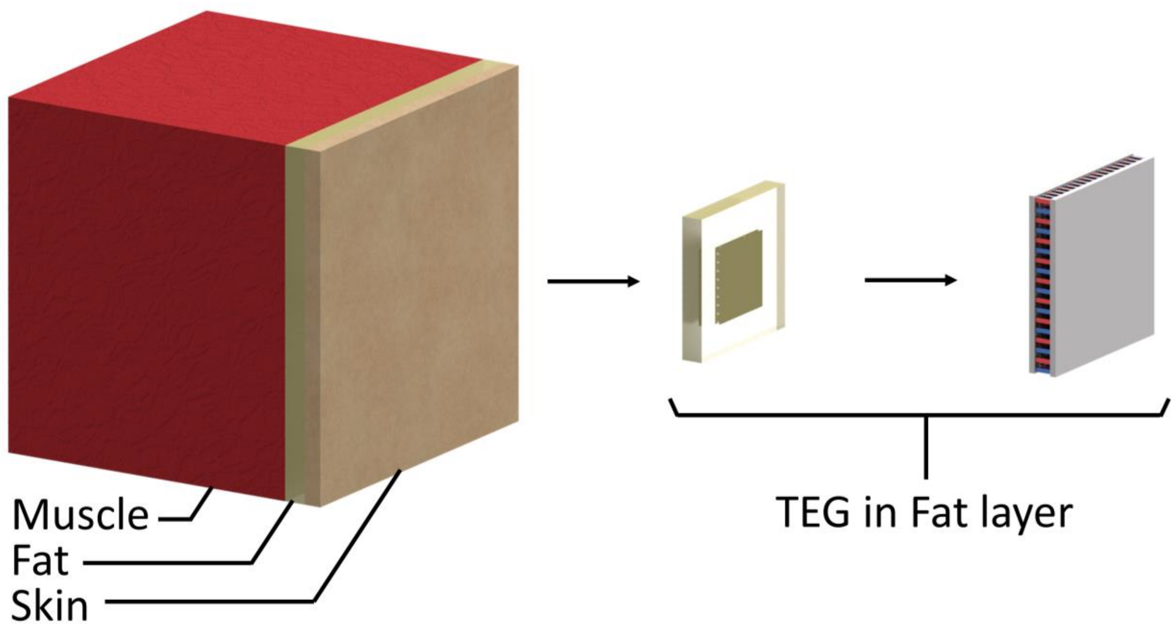


A. Despopoulos and S. Silbernagl, *Color Atlas of Physiology*

Implants and their power needs

Thermoelectric energy harvesting

- How to exploit **thermoelectric energy harvesting in subcutaneous tissue?**
- How to **accurately predict the thermal distribution inside the human body** for optimal TEG operation?



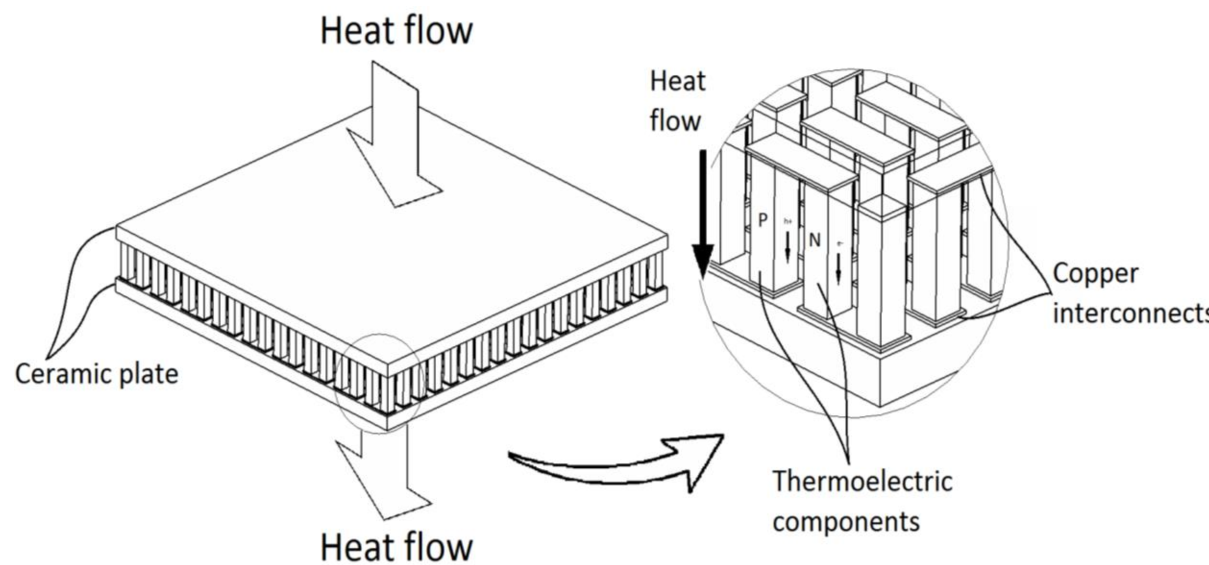
Previous related work – Software lab

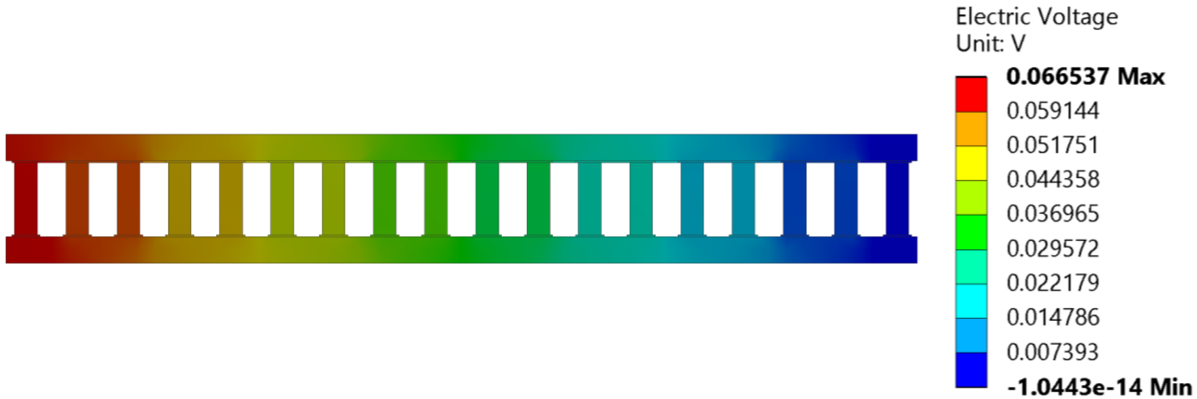
- Modelling and simulation of TEG
- Thermopiles connected thermally in parallel and electrically in series to form a thermocouple
- Open circuit voltage

$$V_{out} = n\,\Delta T\,(\alpha_1 - \alpha_2)$$

- The maximum power delivered into load resistor calculated from:

$$P_{max} = \frac{V_{out}^2}{4R_{el}}$$





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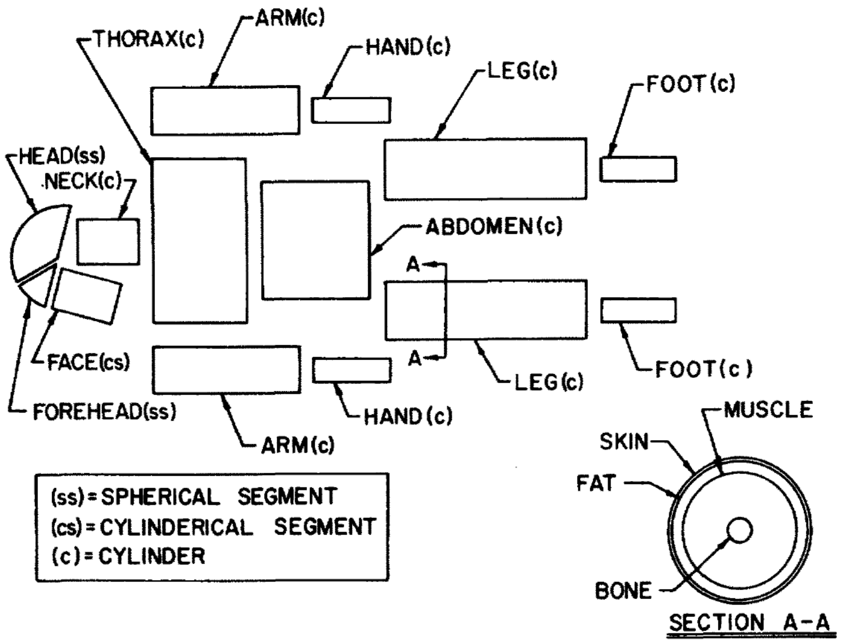
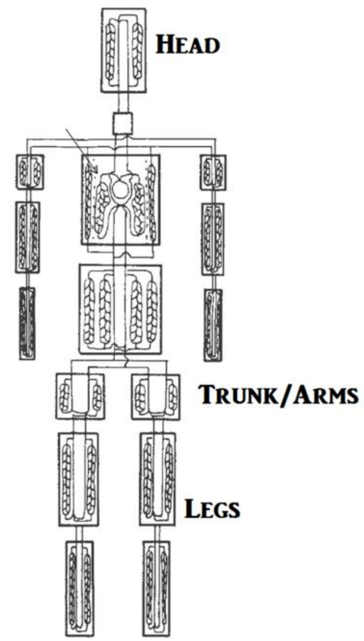
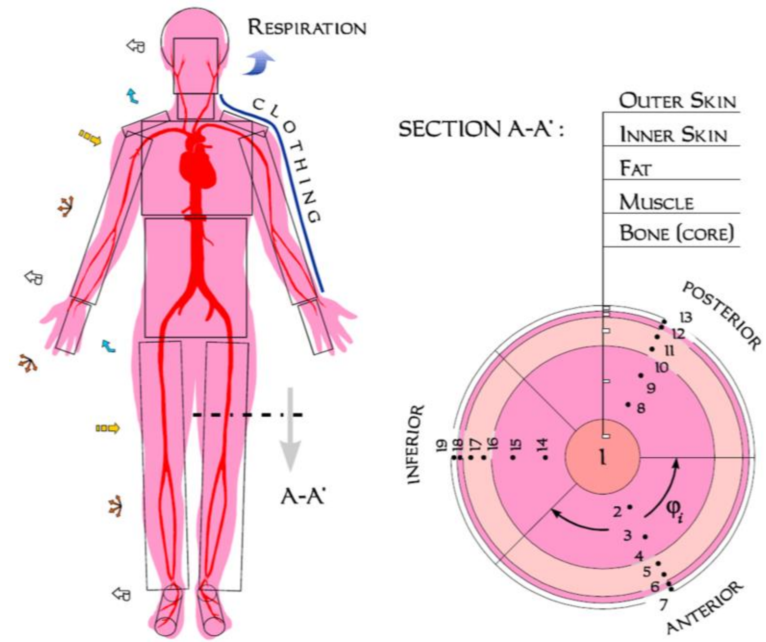
State of the art
Thermal models



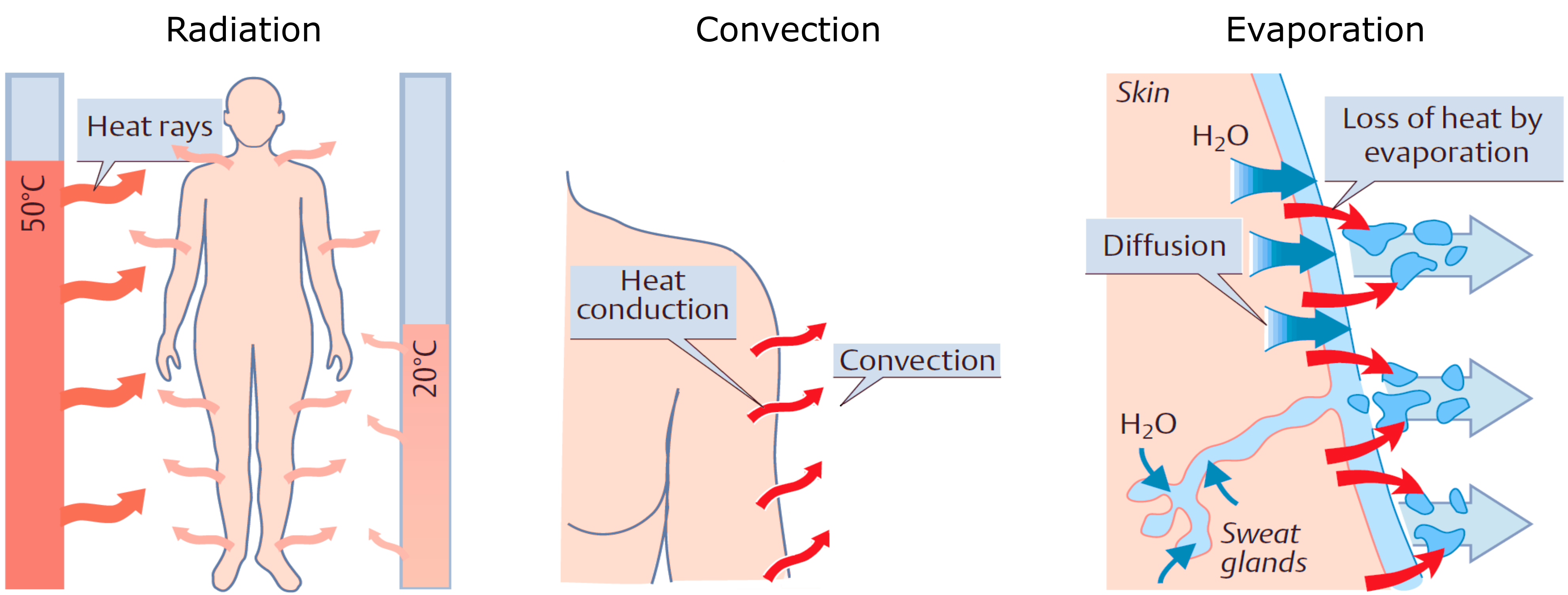




R. G. Gordon, 1976, *IEEE Trans. Biomed. Eng.*, vol. BME-23, no. 6
E. H. Wissler, 1985 *Heat transfer in medicine and biology*, vol. 1, no. 13
D. Fiala, 1988, PhD, Institute of Energy and Sustainable Development, De Montfort University

State of the art

Mechanisms of heat loss



$$-A\kappa \left.\frac{\partial T}{\partial r}\right|_s = \sigma\varepsilon F A_{skin}\left(T_{skin}^4 - T_{amb}^4\right) + h_c A_{skin}\left(T_{skin} - T_{amb}\right) + h_e A_{skin} w\left(P_{sk,s} - P_a\right)$$

[1] Murakami et al., 2000, *Build Environ,* 35, 489-500
R. G. Gordon et al., 1976, *IEEE Trans. Biomed. Eng.*, vol. BME-23, no. 6

State of the art

Bioheat modelling

$$\rho c \frac{\partial T}{\partial t} = \overbrace{\nabla \kappa \nabla T}^{\text{Conduction}} + \underbrace{\rho_b c_b \omega_b (T_{artery} - T)}_{\text{Perfusion}} + \overbrace{Q_m}^{\text{Metabolic heat}}$$

Pennes' bioheat equation considers:

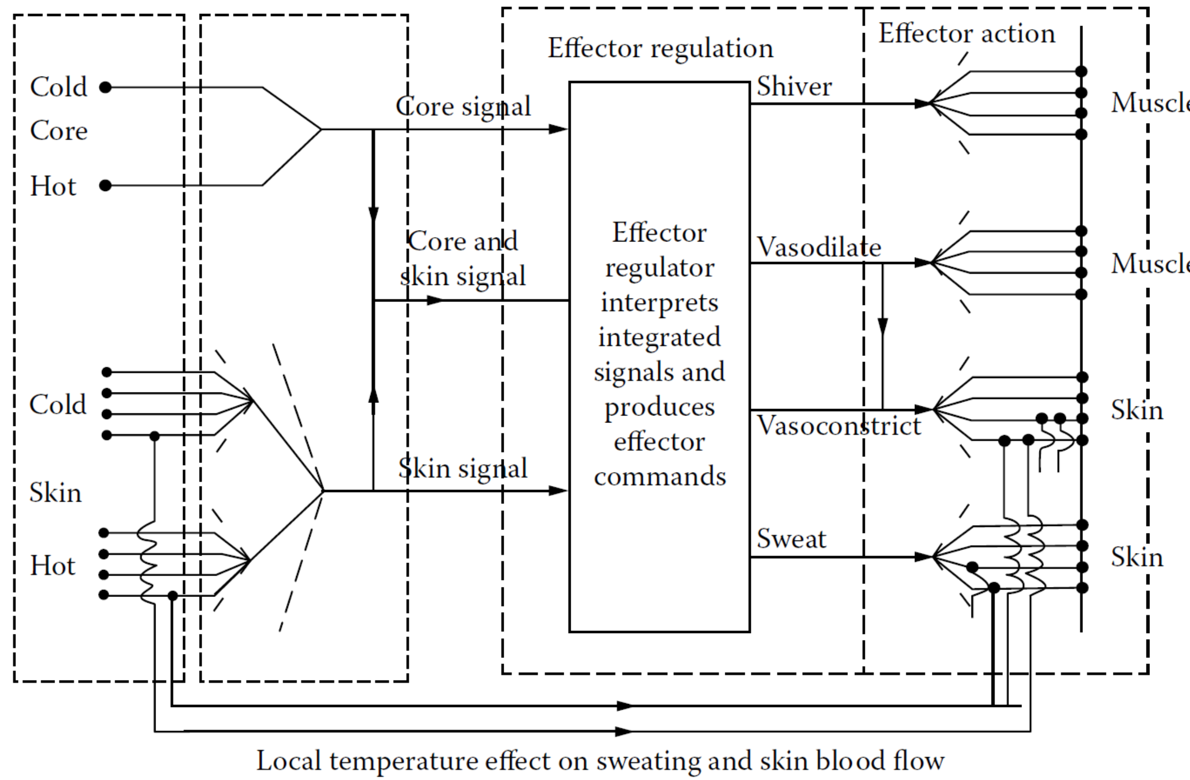
- Heat conduction
- Blood perfusion
- Metabolic heat generation

H. H. Pennes, 1948, *Journal of applied physiology*, Vol. 1, no. 2

State of the art

Thermoregulation

- Thermoregulatory reflexes
  - active thermal system
  - maintains core temperature at 37 °C.
- Thermoreceptors
  - sense temperature on core and skin
  - send signal to hypothalamus
- Effector mechanism
  - sends regulatory control signals



J. J. A. Stolwijk et al., 1977, *Handbook of Physiology, American Physiological Society*

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Simulation methodology

Assumptions:

- No blood flow
- Blood vessels fixed at 37 °C
- Tissue materials - isotropic
- Bioheat modelled using Pennes' bioheat equation
- Metabolic heat generation applied to entire tissue

Tissue	**Density** ρ, **(kg/m³)**	**Specific heat** c, **(J/(kg K))**	**Thermal conductivity** κ, **(W/(m K))**	**Min. Heat Generation Rate (W/m³)**	**Min. Heat Transfer Rate (1/s)**
Muscle	1090.40	3421.2	0.494	498.5245	0.000337
SAT (Subcutaneous Fat)	911.00	2348.3	0.211	279.8010	0.000301
Skin	1109.00	3390.5	0.372	841.5733	0.000906

P. A. Hasgall *et al.*, "IT'IS Database for thermal and electromagnetic parameters of biological tissues," www.itis.ethz.ch/database

Simplified cubic human tissue

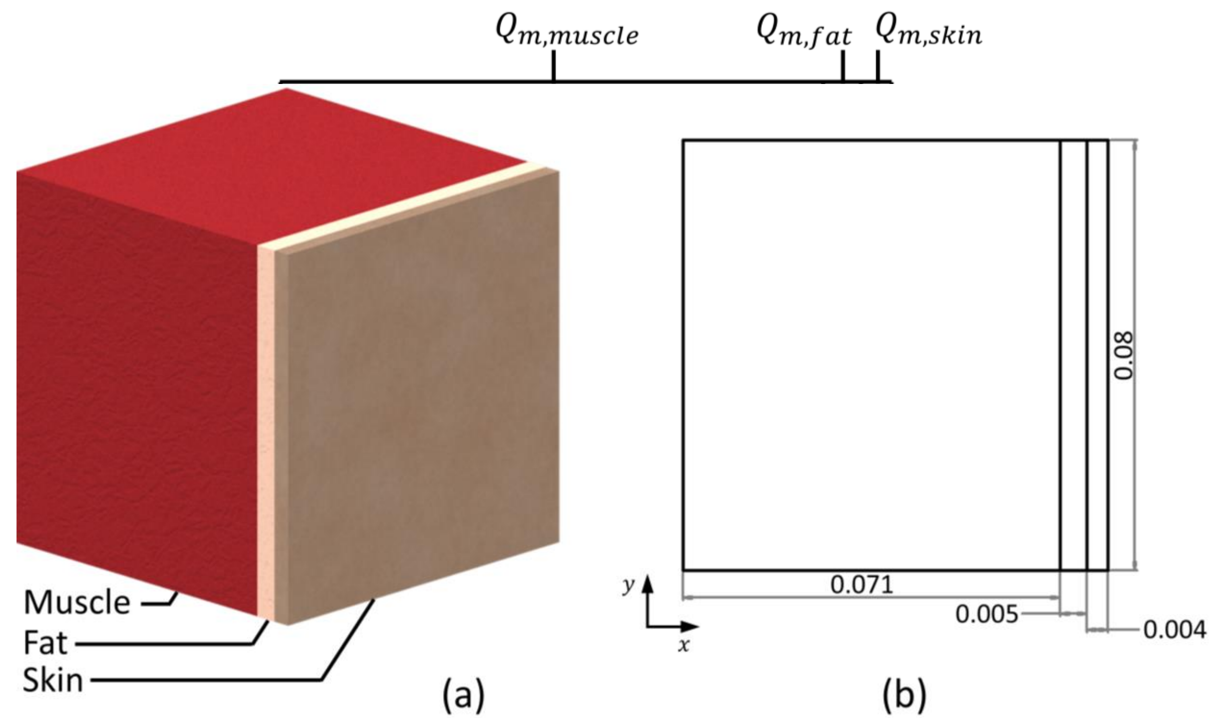
- Computational domain: 0.08 m × 0.08 m × 0.08 m
- Three tissue layers: muscle, fat and skin

Metabolic heat generation:

$$Q_{m,muscle}, Q_{m,fat}, Q_{m,skin}$$

as a body force element

Body core perfectly insulated
Radiation: $\varepsilon = 0.95$
Convection: $h_c = 3.1$ W/m^{2}K
Evaporation: $w = 0.06$
Ambient temperature: 15 °C

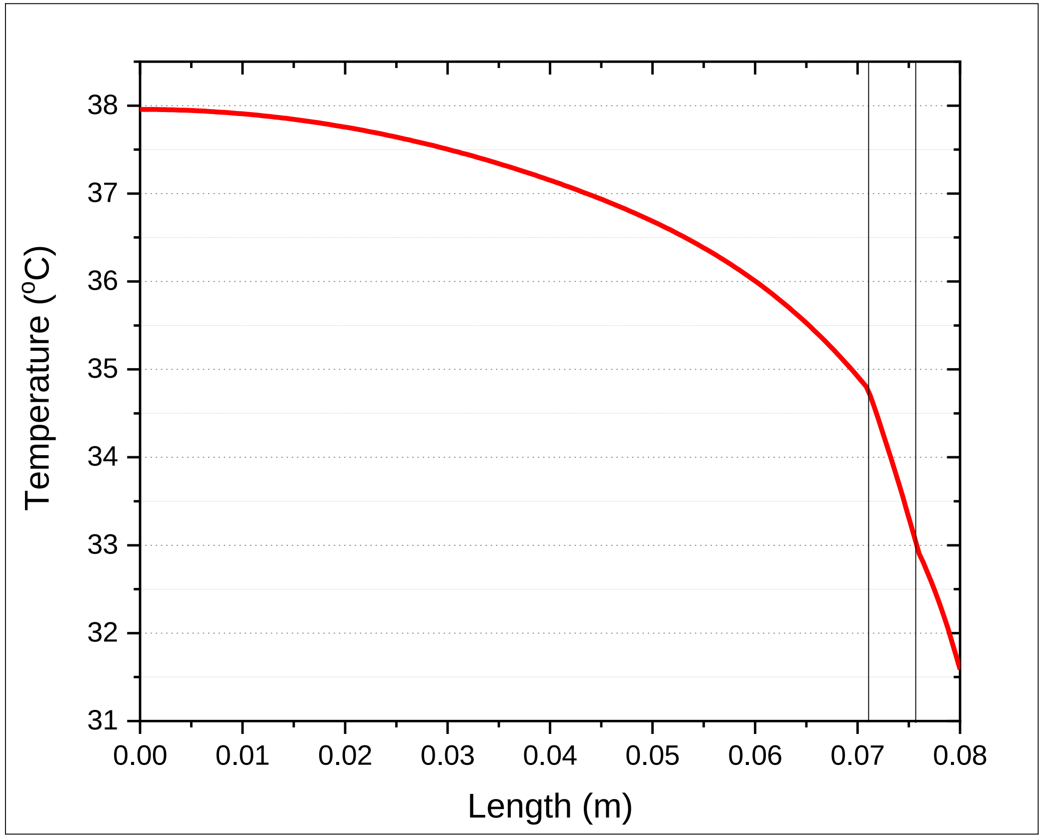


Y. Yang et al, 2007 ,*Phys. D: Appl. Phys.*, Vol. 40, no. 18

Simplified cubic human tissue

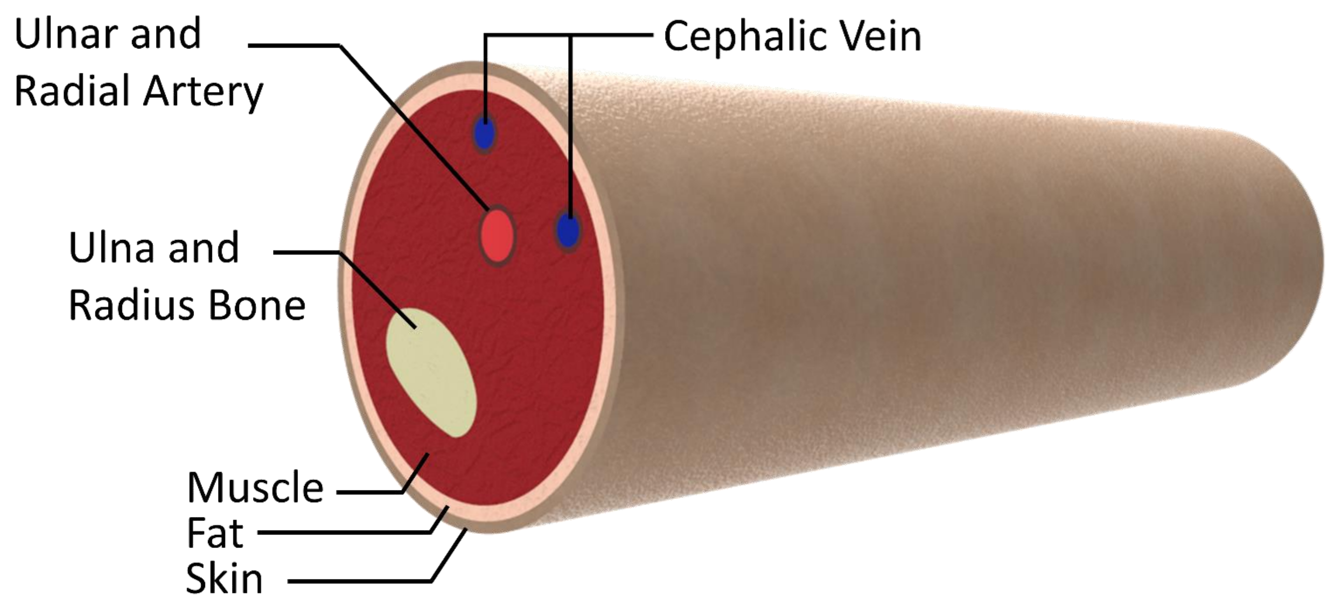
Results

- Insulating effects of the fat layer
- Temperature drop: 1.6 K
- Core temperature rises above 37 °C
- High heat generation from bioheat equation due to large muscle thickness



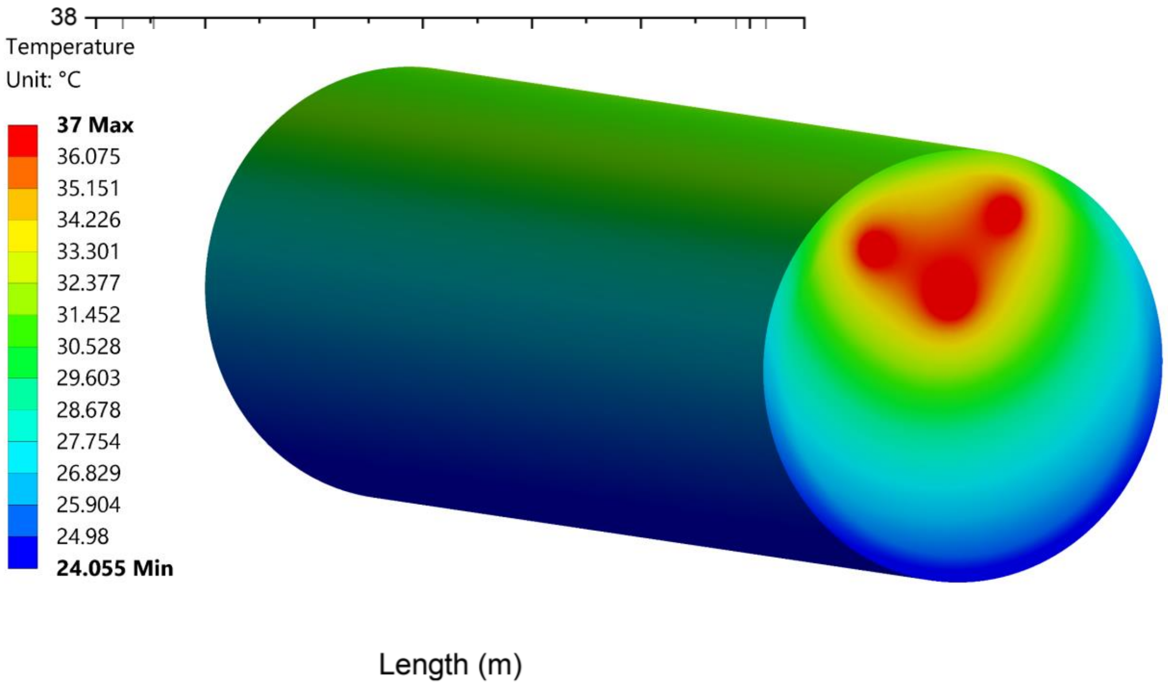
Simplified human forearm

- Concentric tissue structure with off-center blood vessels and bone
- Dirichlet boundary, 37 °C applied on blood vessel bodies
- Similar boundary conditions as cubic model



Simplified human forearm

Results



- Heat flows from the blood vessels to the skin surface
- Skin surface temperature near the top skin surface is higher
- Temperature drop across fat layer
- Realistic muscle volume, no observable rise in temperature above 37 °C

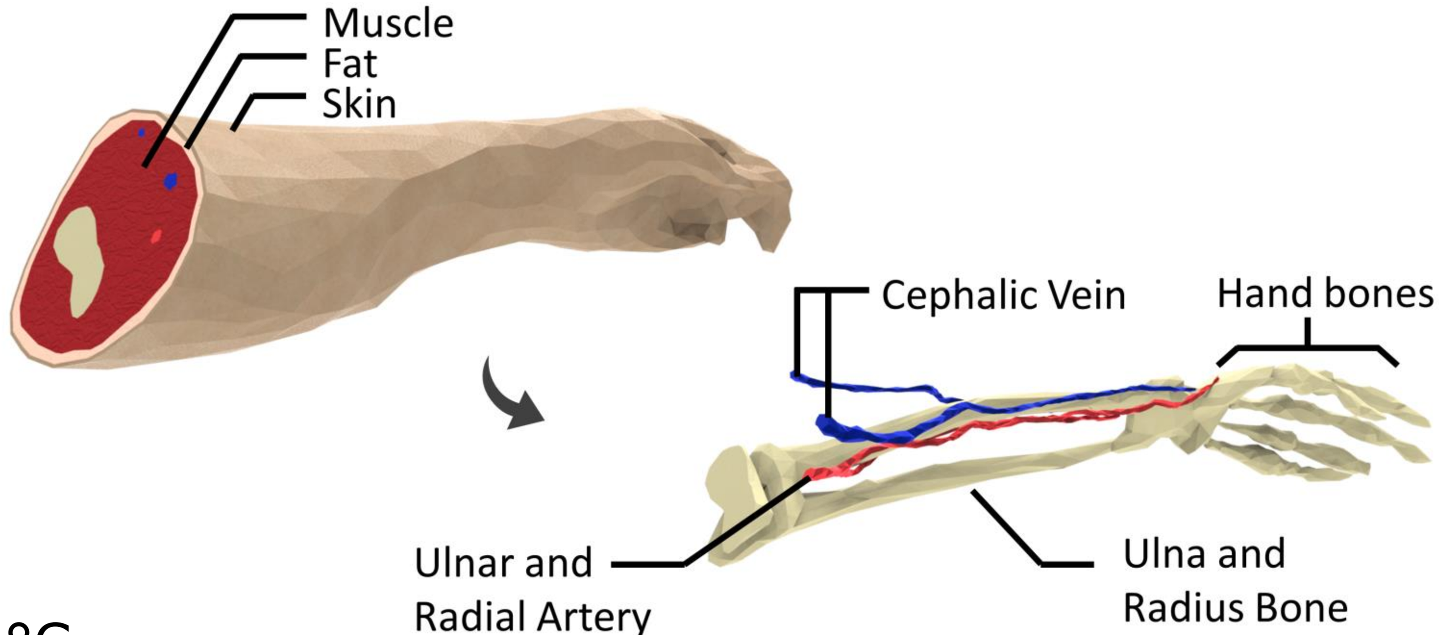
Human forearm

Separated below the elbow from realistic human body geometry

Metabolic heat generation:

$$Q_{m,muscle}, Q_{m,fat}, Q_{m,skin}$$

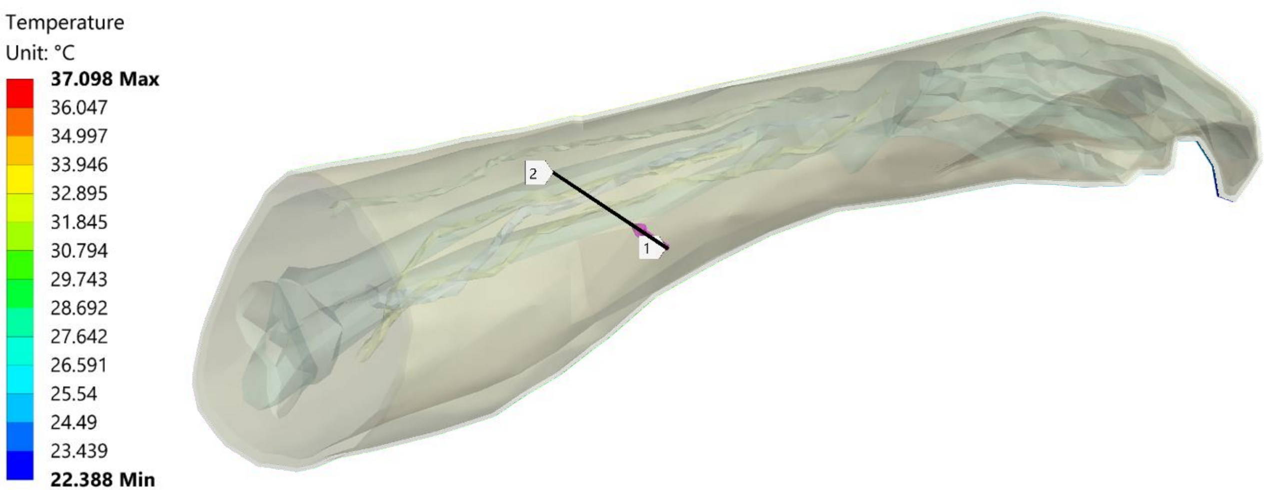
Blood temperature: 37 °C
Radiation: $\varepsilon = 0.95$
Convection: $h_c = 3.1$ W/m^{2}K
Evaporation: $w = 0.06$
Ambient temperature: 5 °C - 35 °C

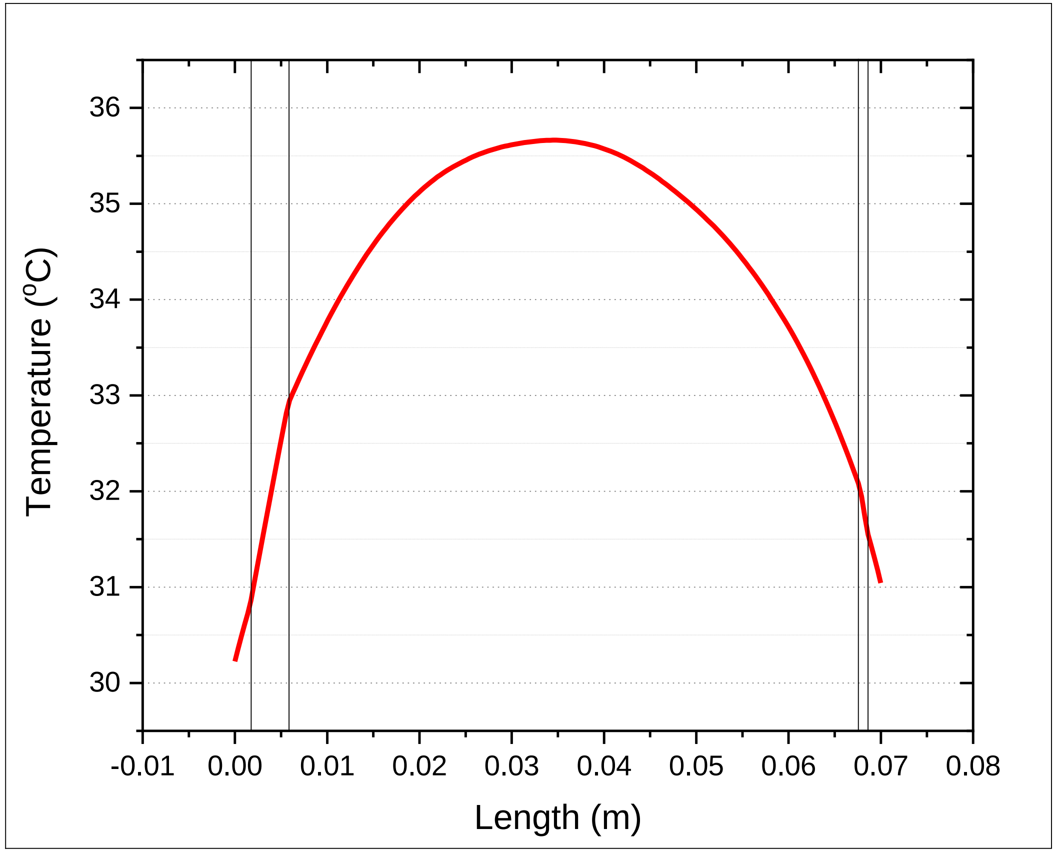


Human forearm

Results

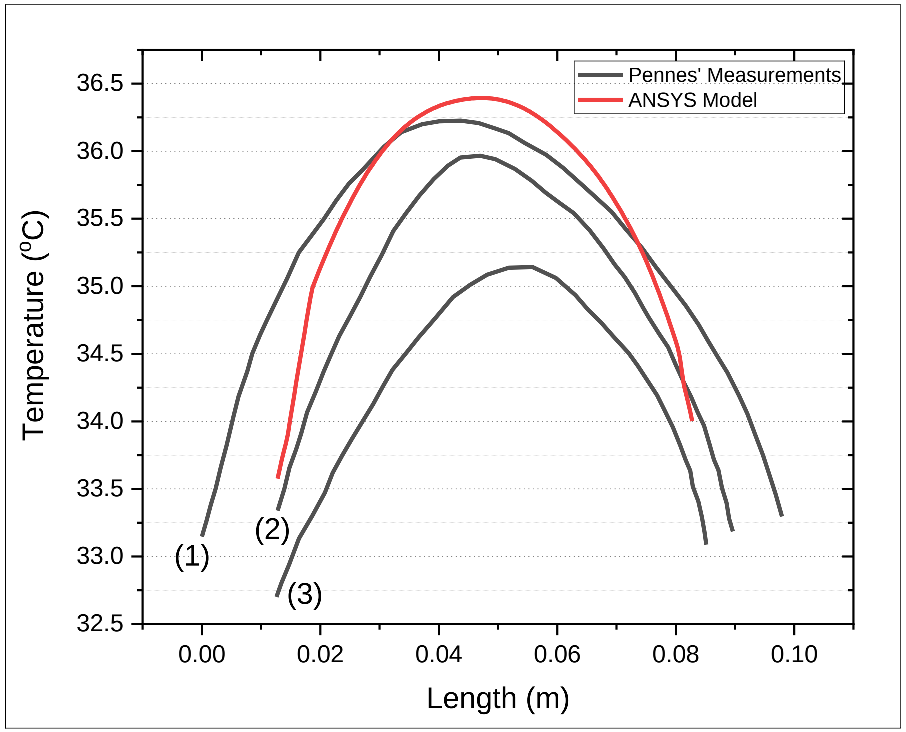
- The fingers show low temperature as a response to cold environment (15 °C)
- Wrist region, shows higher temperature (hot spot) close to the skin



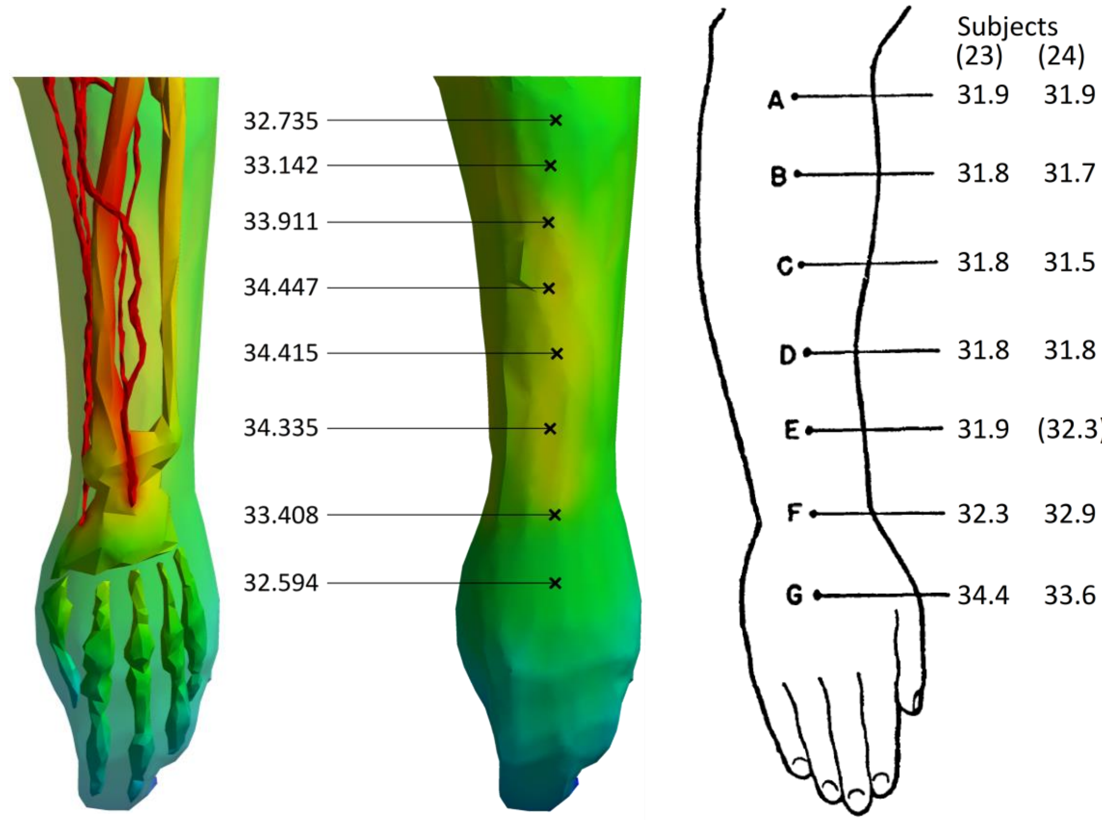


Human forearm

Results



Temperature profile compared with Pennes' measured values, T_{amb}= 26.6 °C

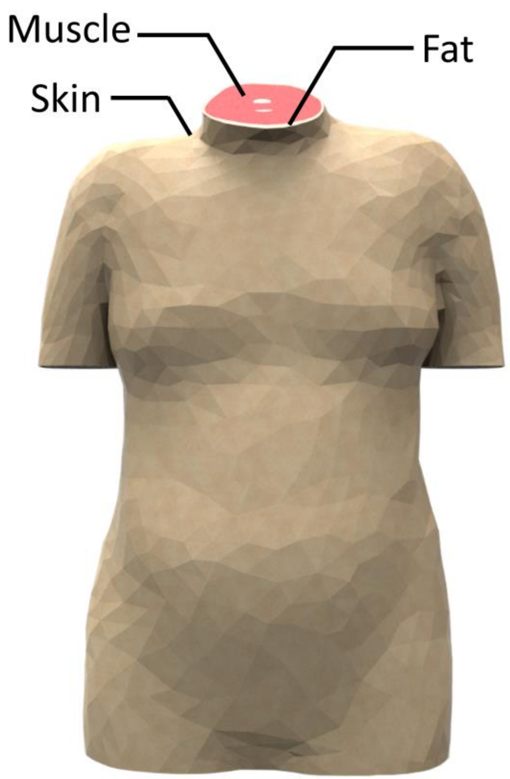


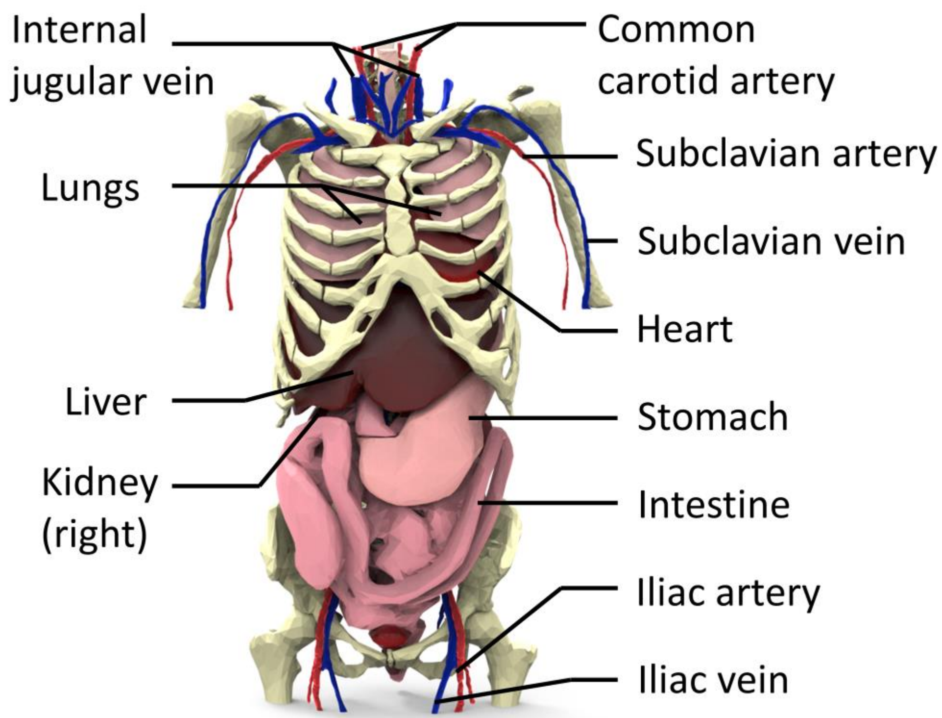
Surface temperatures along the long axis, T_{amb}= 25 °C

H. H. Pennes, 1948, *Journal of applied physiology*, Vol. 1, no. 2

Human torso

The model is comprised of 108 individual parts including the bones, cartilage, vascular network and internal organs





Human torso

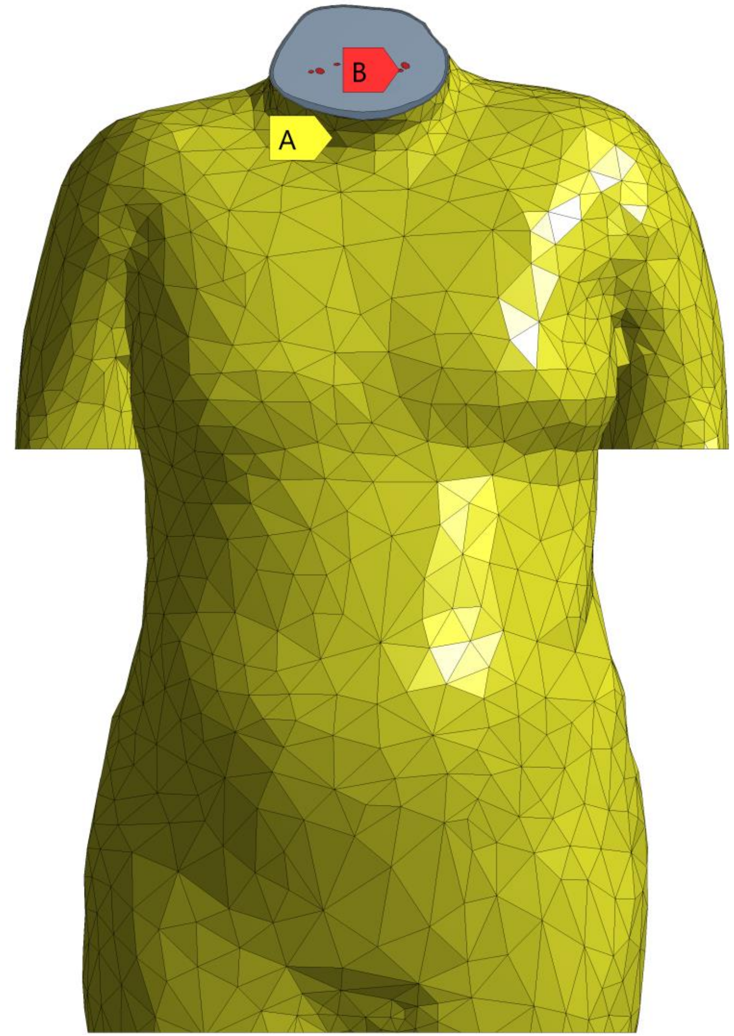
Metabolic heat generation adjusted to solid volume of internal organs
(heart, lungs, stomach etc.)

A Radiation: $\varepsilon = 0.95$
Convection: $h_c = 3.1$ W/m²K
Evaporation: $w = 0.06$
B Blood temperature: 37 °C

Ambient temperature: 15 °C
Metabolic heat generation:

$$Q_{m,muscle}, Q_{m,fat}, Q_{m,skin}$$

and other organs

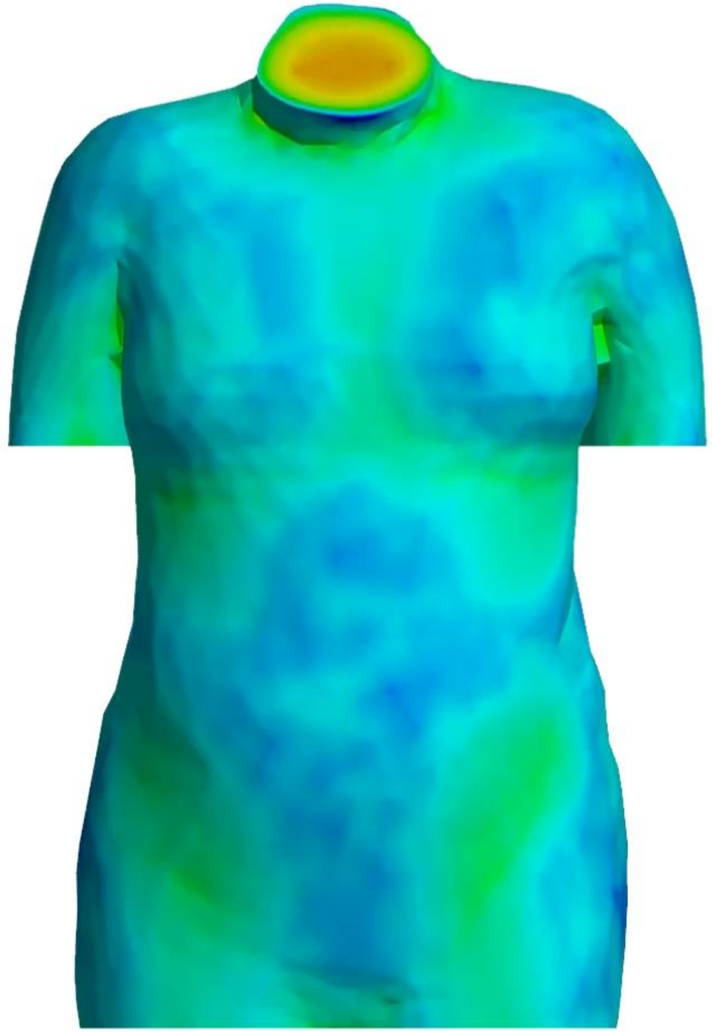


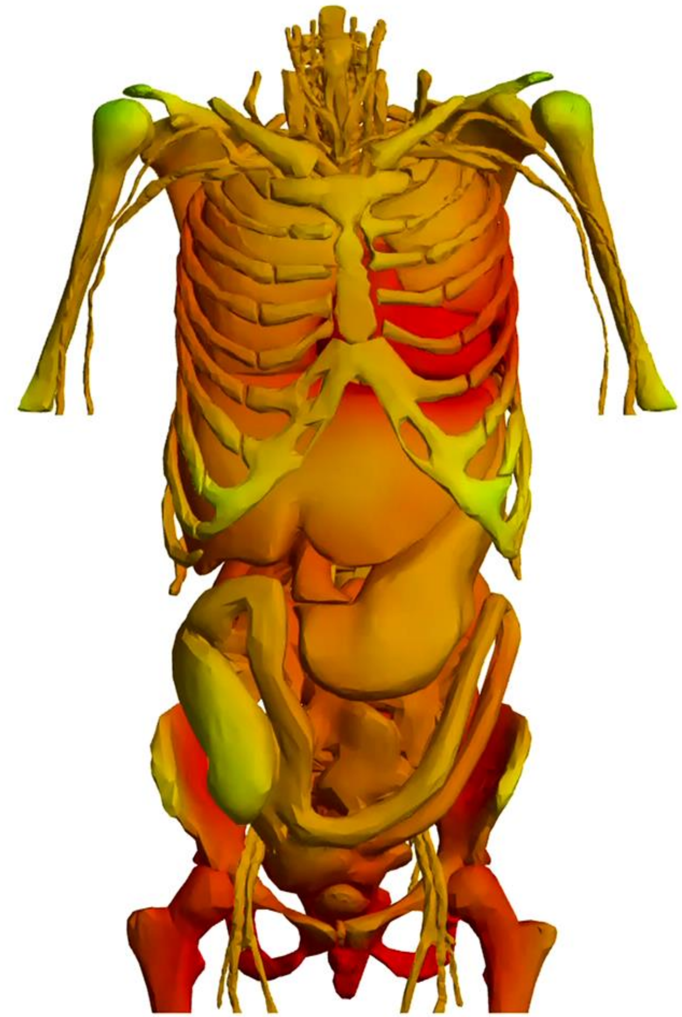
Human torso

Results

Temperature
Unit: °C

39.108 Max
38.5
37.603
36.706
35.809
34.912
34.015
33.118
32.221
31.324
30.428
29.531
28.634
27.737
26.84 Min

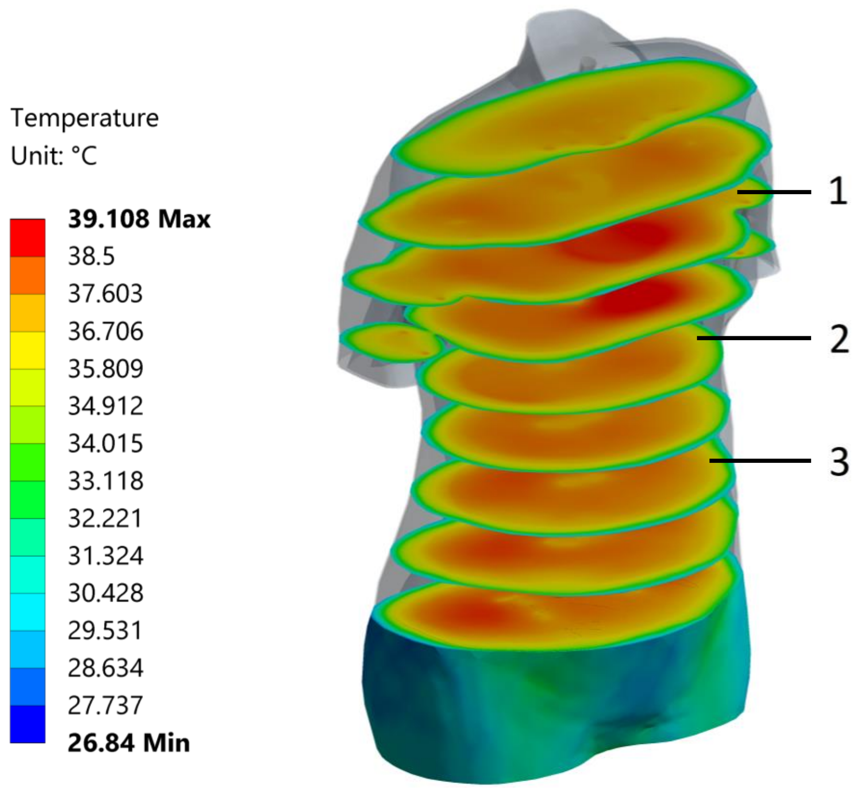


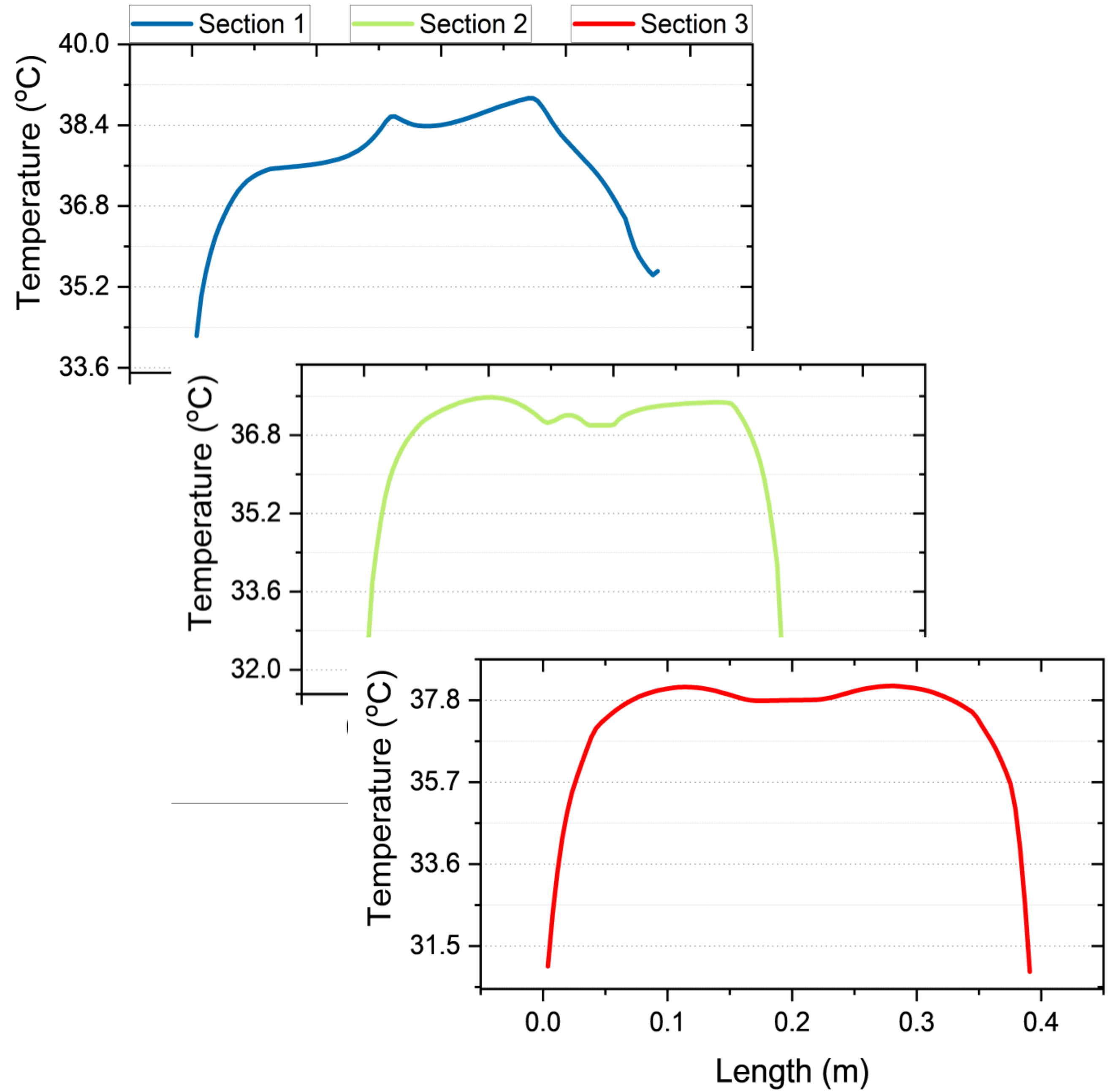


Human torso

Results

Temperature distributions across various sections highlight favorable locations for the TEG-powered implants

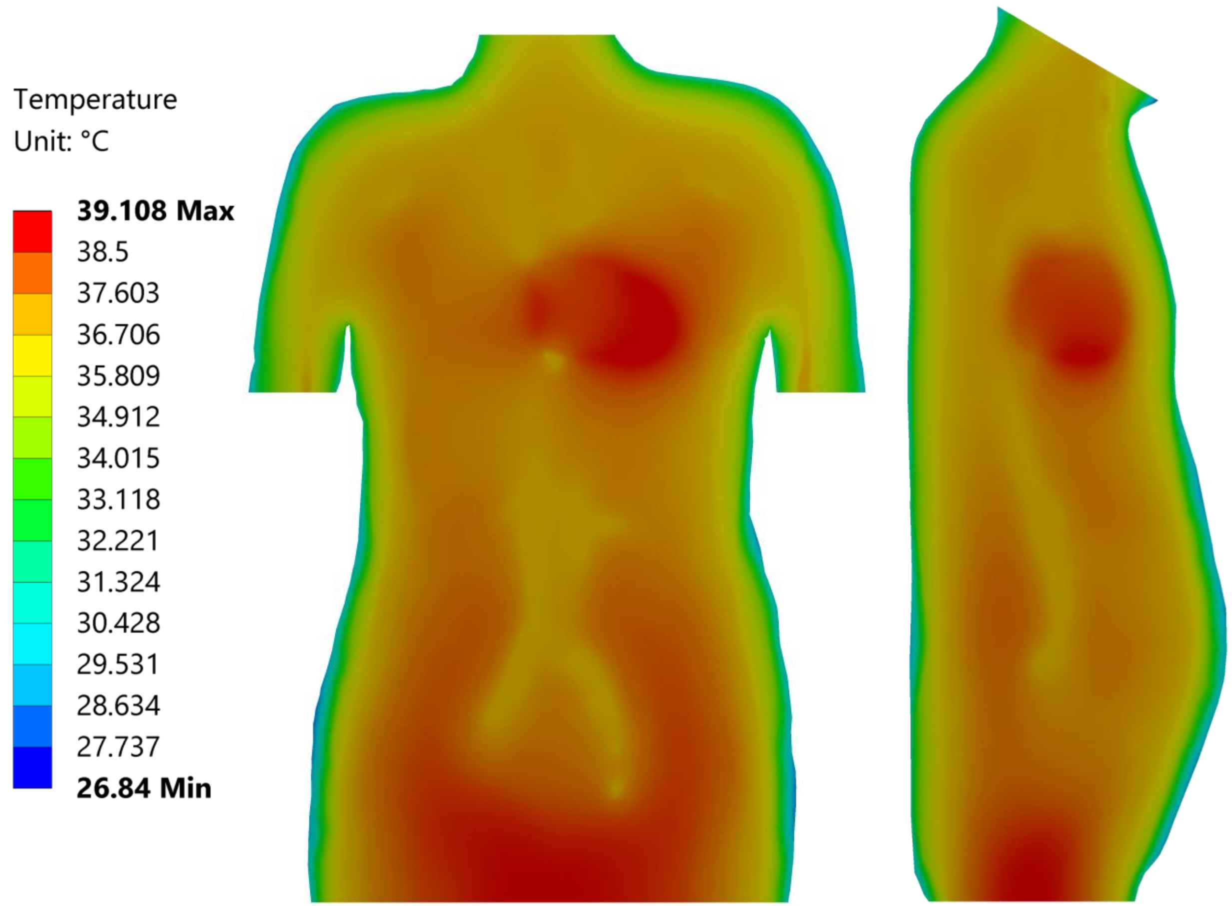




Human torso

Results

- High temperature gradients
  - chest
  - lower left and right abdomen
- Moderate temperature drops
  - upper shoulder region for low profile implants



Human torso

Limitations

- Solid organs instead of thin walled
- Highly faceted irregular geometry
- Difficulty in generation of smooth mesh
- Temperature rises above 37 °C in heart and lower abdomen

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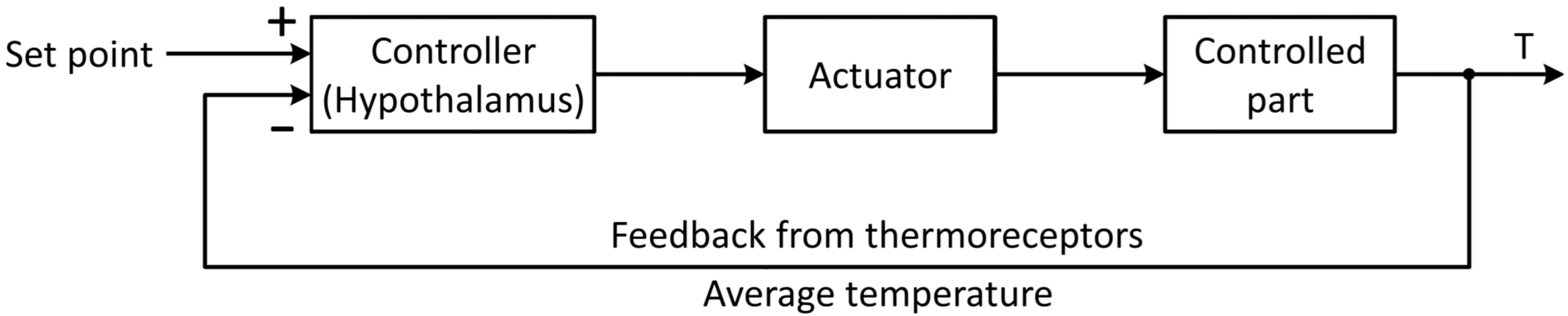
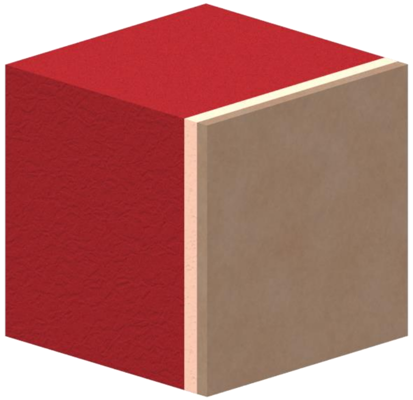
Thermoregulation in simplified cubic model

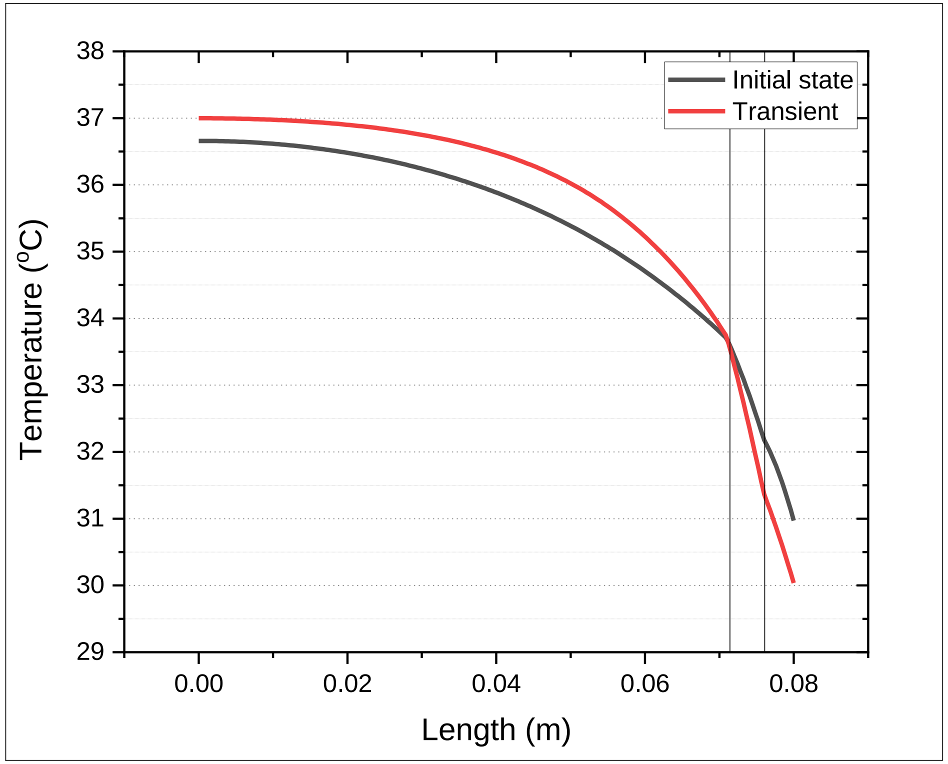




Controller	Control action	Physiological action	Controlled part
I	Blood perfusion rate	Metabolic heat generation	Muscle
II	Blood perfusion rate	Vasoconstriction/-dilation	Skin
III	Skin wettedness	Sweating	Skin

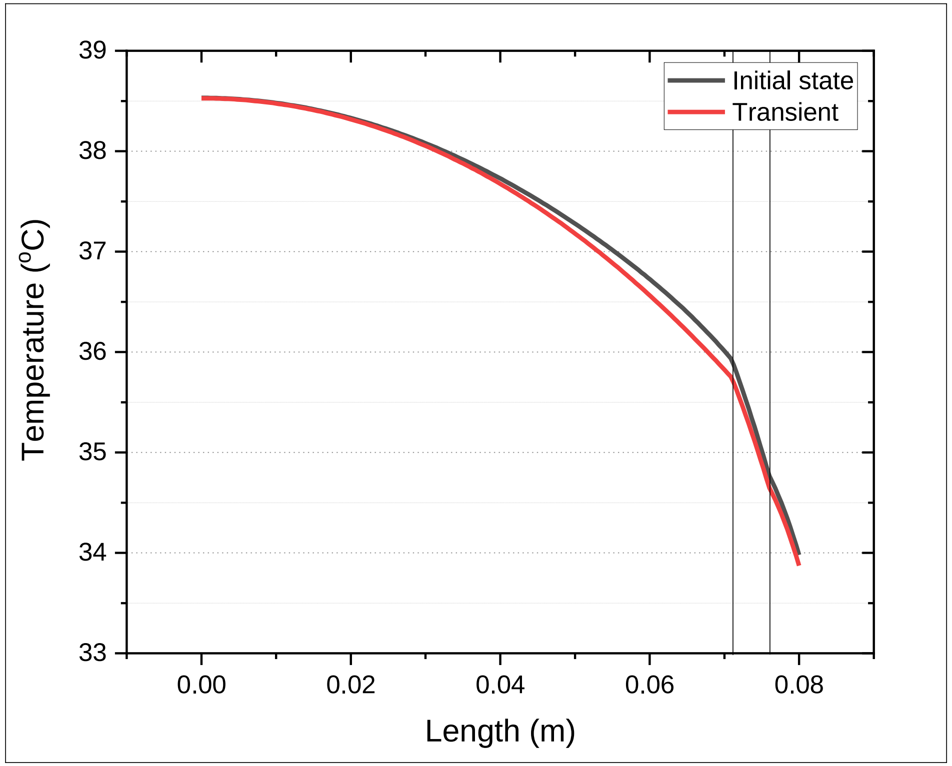
Thermoregulation in simplified cubic model

Results



$$T_{amb} = 15\,°C$$

Core temperature : 36.6 °C to 37 °C
Skin temperature : 31 °C to 30.04 °C



$$T_{amb} = 25\,°C$$

Core temperature : constant at ~38.5 °C
Skin temperature : 34 °C to 33.87 °C

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Conclusion

- Active and passive systems analyzed with various heat transfer and regulatory mechanisms
- Bioheat equation modelled for various tissues
- Stationary analysis shows maximum temperature drop present across fat layer
- Active sweating and vasoconstriction/-dilation implemented using proportional control

Outlook

- Sourcing human body geometry with better resolution would allow for physiologically accurate analysis
- Including shivering and respiration as additional heat loss mechanisms
- Analyzing implant itself complete with the TEG, battery and supporting electronics in a hermetically sealed housing under physiological conditions
- Possible integration of the bioheat model with thermal comfort effects in enclosed environments such as buildings, transportation etc.

Thank you for your attention!