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Comparing the Muscular Efficiency of Going Up and Down Hills

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A simple measurement of the relative efficiency of human locomotion

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Abstract
Elementary formulas for gravitational potential energy, heat capacity, and Newton's law of cooling are used to measure and compare the efficiencies of a person walking uphill and downhill. Good agreement is found for their ratio with more sophisticated experiments in the literature made by measuring respiration to determine metabolic power. A simple argument explains why human muscles are less than 50% efficient at converting chemical into mechanical energy.

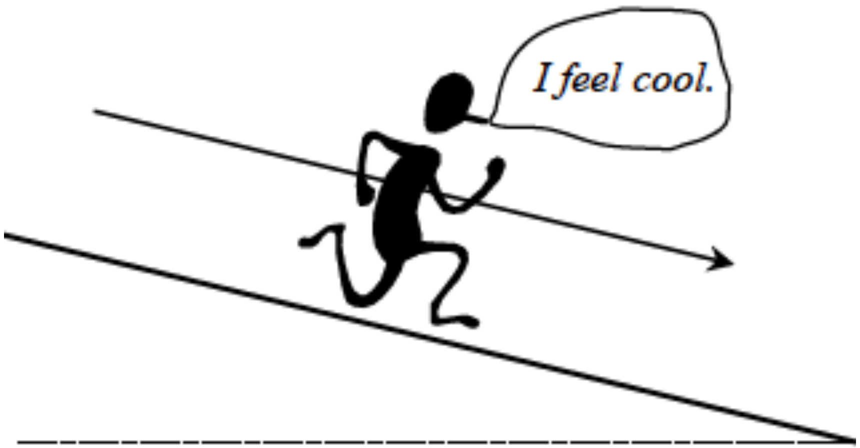
THE HUMAN BODY AS A HILL-CLIMBING MACHINE

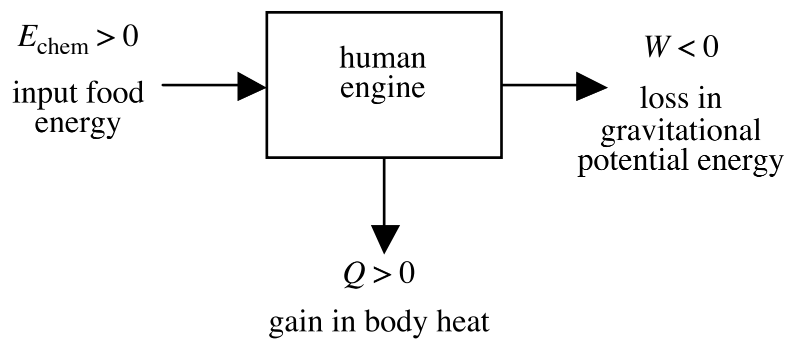
efficiency $$\boxed{\varepsilon \equiv \frac{W}{E_{\text{chem}}}} = \frac{1}{1+\kappa}$$

coefficient of performance $$\boxed{\kappa \equiv \frac{Q}{W}}$$

Both ε and κ are positive for uphill walking,
and both are negative for downhill walking.

GOING DOWNHILL

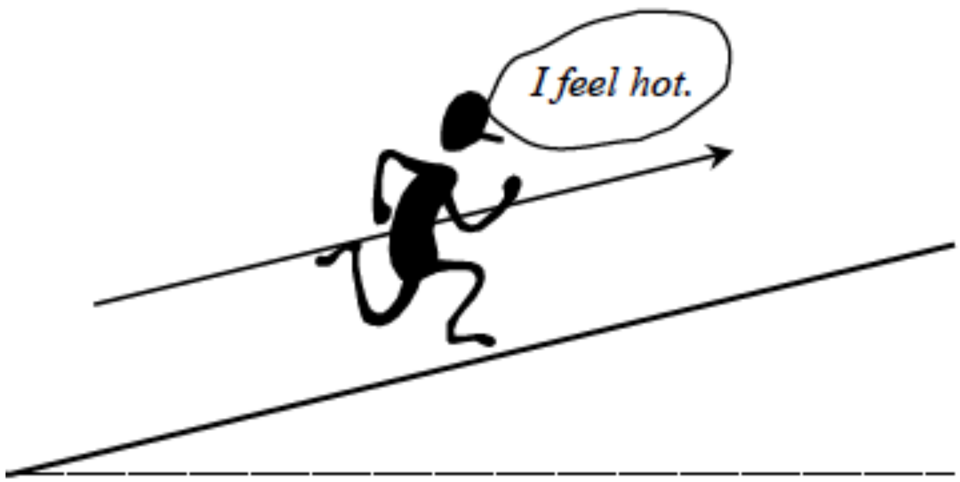


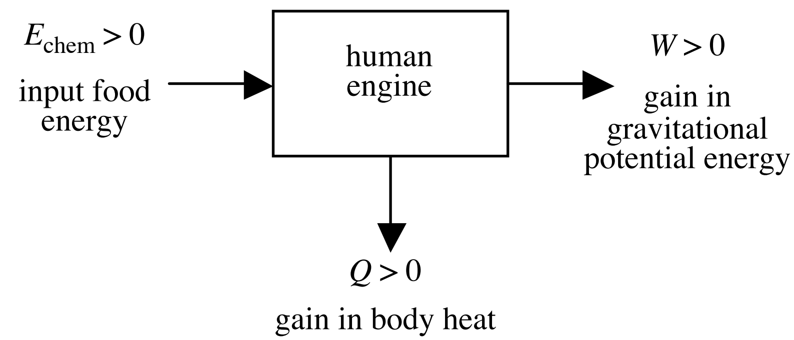


Ideally $E_{\text{chem}} = 0$ and so $\kappa_{\text{downhill}} = -1$.

In reality, muscles do work to control one's descent, and so $\kappa_{\text{downhill}} = -1.8$.

GOING UPHILL





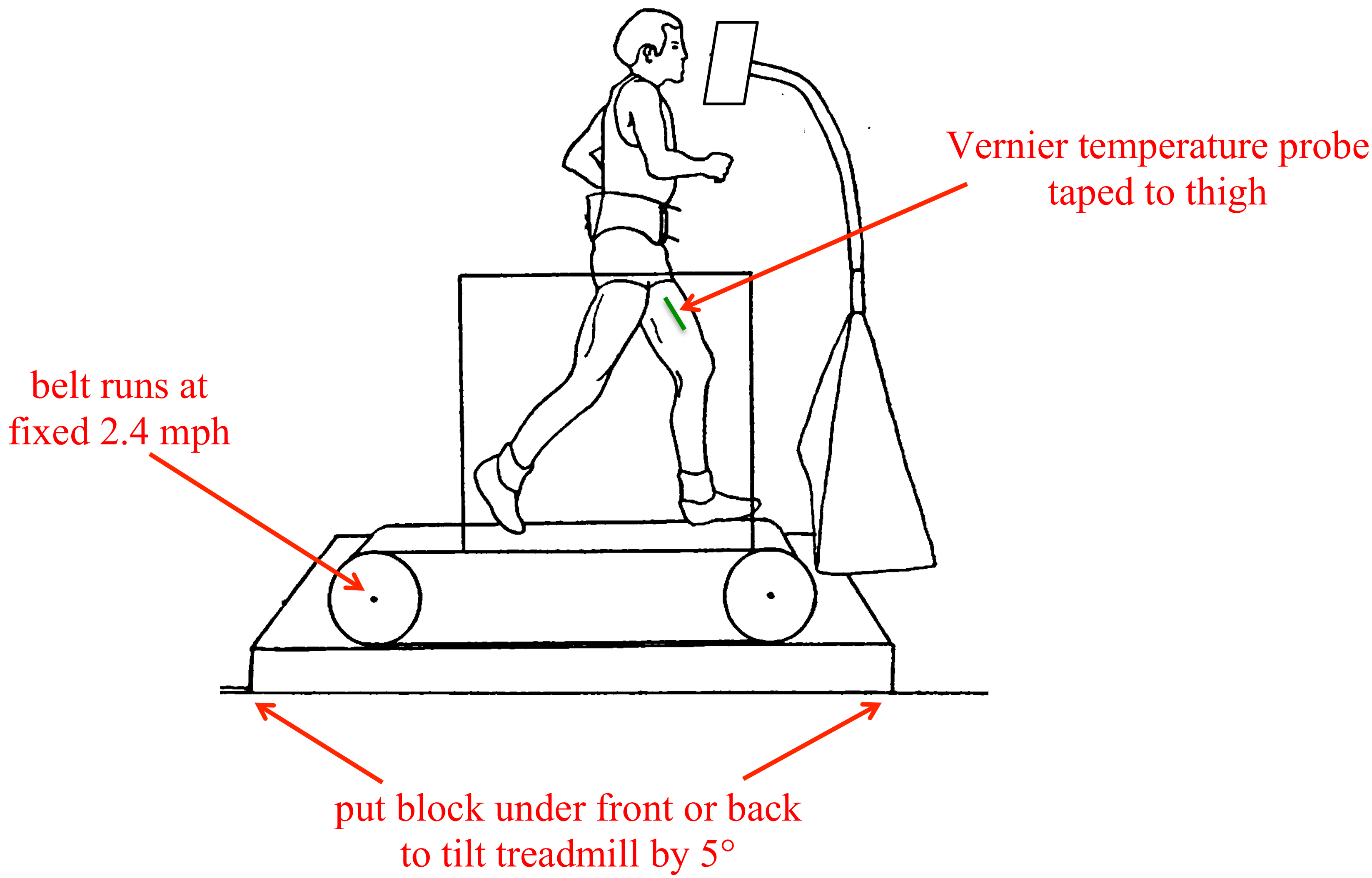
A person gets hotter going up than down the same hill at the same rate.

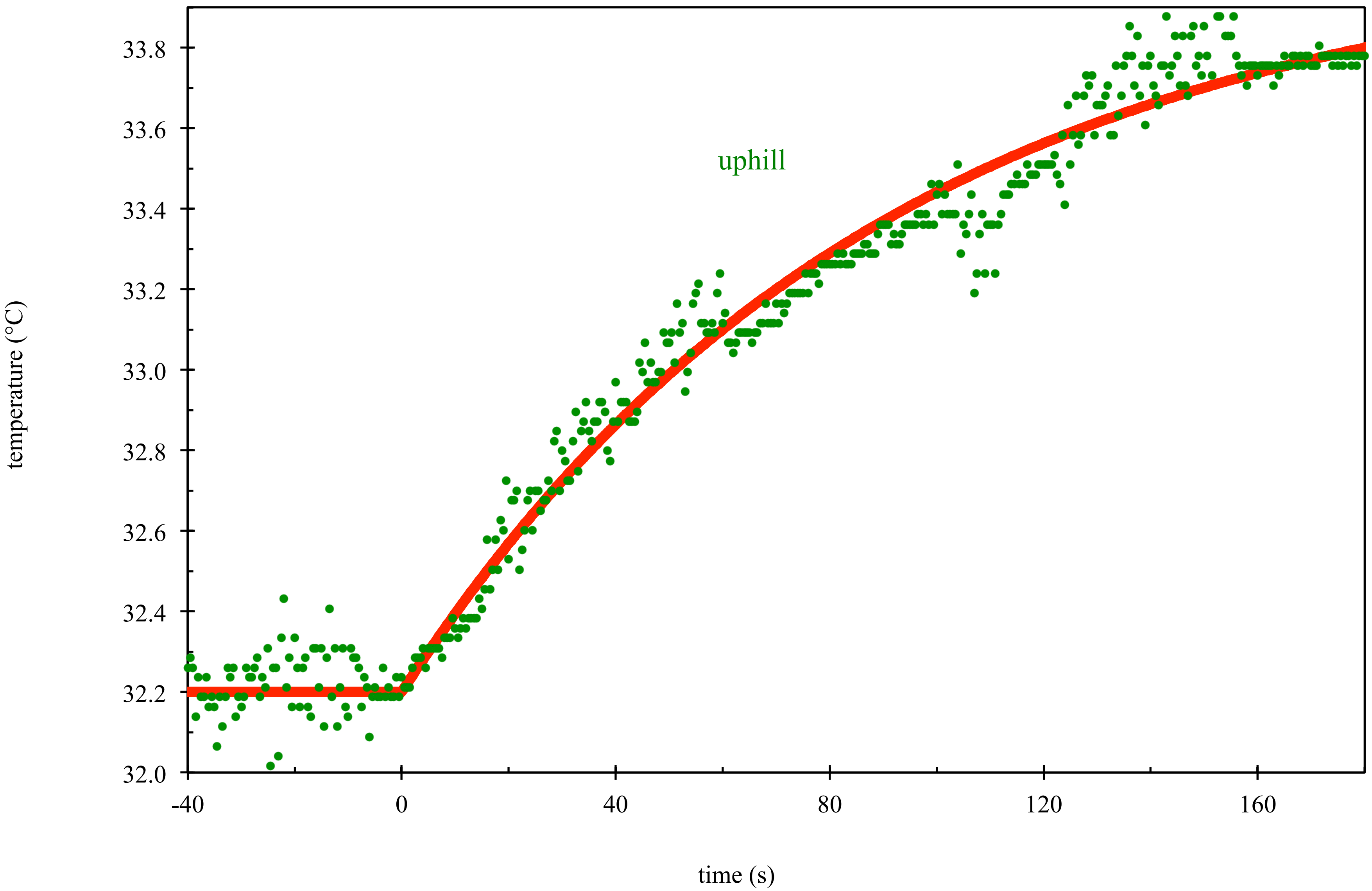
Thus even ideally, $\kappa_{uphill} > |\, \kappa_{downhill} \,| \geq 1$ and so $\varepsilon_{uphill} < 1/2$.

Human hill-climbing efficiency must be less than 50%.

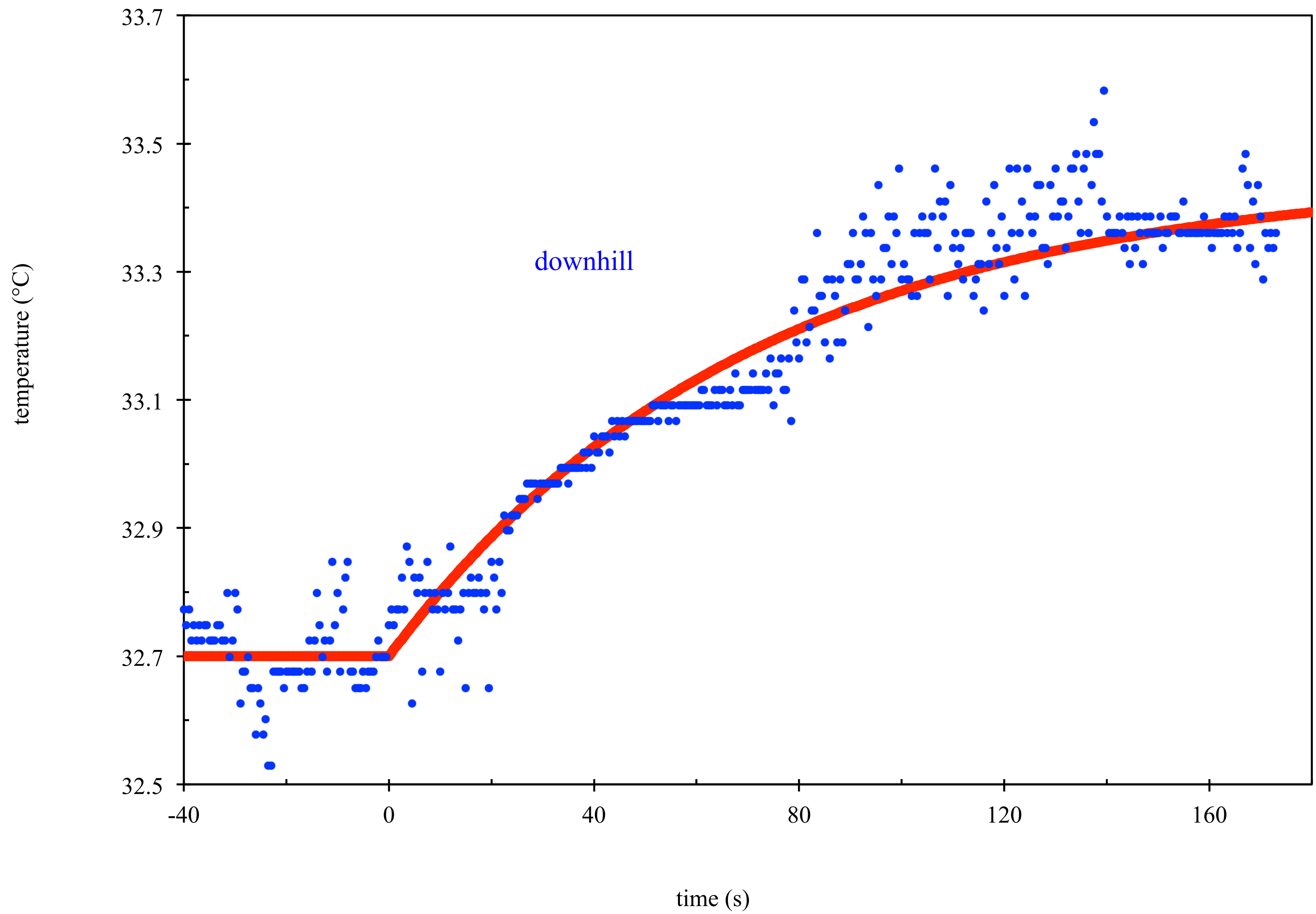
In reality $\varepsilon_{uphill} = 25\%$.

MEASURE LEG TEMPERATURE RISE VERSUS TIME





Based on Newton's law of cooling, fit the saturating exponentials shown as the red curves.



33.7
33.5
33.3
33.1
32.9
32.7
32.5
temperature (°C)
downhill
-40
0
40
80
120
160
time (s)

ANALYSIS

$$\boxed{\kappa = \frac{\dot{Q}}{\dot{W}} = \frac{c\dot{T}_{\text{initial}}}{g\upsilon\sin\theta}}$$

$$c = \text{specific heat of thigh} = f \cdot c_{\text{body}}$$

$$\begin{cases} f = m_{\text{thigh}} \big/ m_{\text{body}} \approx 4\% \\ c_{\text{body}} = 3570 \text{ J/kg/°C (bit less than water)} \end{cases}$$

where $\dot{T}_{\text{initial}} = (T_{\text{f}} - T_{\text{i}}) \big/ \tau$

$$\begin{cases} T_{\text{i}} = \text{ambient temperature of thigh} \\ T_{\text{f}} = \text{final saturated temperature} \\ \tau = \text{exponential time constant} \end{cases}$$

$$g = 9.8 \text{ m/s}^2$$

$$\upsilon = 2.4 \text{ mph} = 1.1 \text{ m/s}$$

$$\theta = \pm 5^\circ$$

CONCLUSIONS

IPLS lab experiment that teaches the concepts of gravitational potential energy, engine efficiency, heat capacity, curve fitting, and Newton's law of cooling.

Good agreement with more sophisticated techniques in the physiology literature.

Austin R Comeford is a just-graduated Midshipman from the United States Naval Academy majoring in physics. He will be joining the Navy's submarine force shortly. He was the treadmill subject.

Professor Nathaniel R Greene teaches physics at Bloomsburg University of Pennsylvania. He enjoys implementing energy projects.

Professor Carl E Mungan was the research advisor for Midshipman Comeford. This project was motivated by email discussions initiated by Professor Greene.