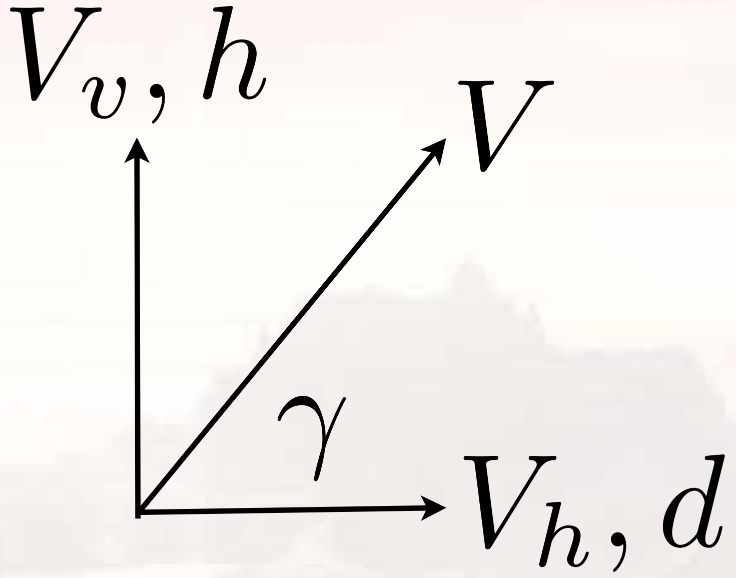
Gaits and Locomotion

- Locomotion
- Metabolic energy
- Gaits
- Partial gravity simulation

Hopping (Airless Flat Planet)



Use *F*=*ma* for vertical motion

$$\dot{V}_v = -g \qquad h = V_v t - \frac{1}{2} g t^2$$

$$t_{flt} = 2V_v/g$$

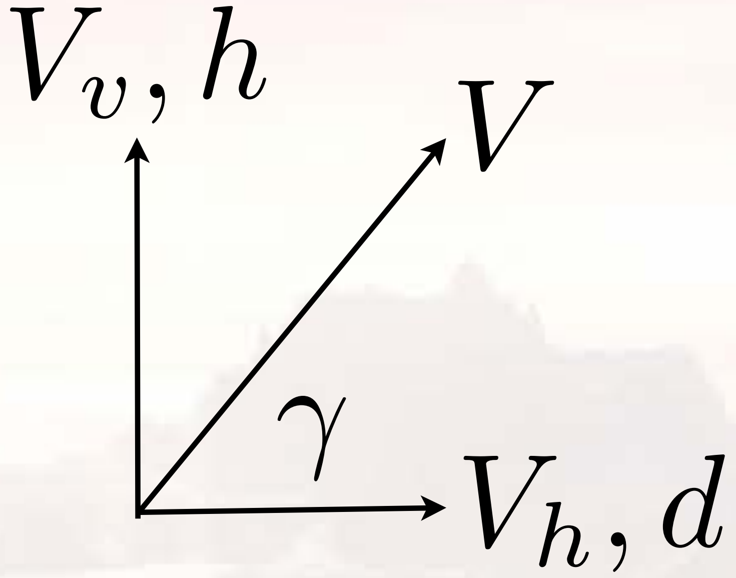
Constant velocity in horizontal direction produces

$$d = V_h t_{flt} = 2\frac{V_h V_v}{g}$$

$$V_h = V\cos\gamma; V_v = V\sin\gamma$$

$$d = 2\frac{V^2 \sin\gamma\cos\gamma}{g} = \frac{V^2}{g}\sin(2\gamma)$$

Hopping (Airless Flat Planet)



Horizontal distance is maximized when $\sin(2\gamma) = 1$

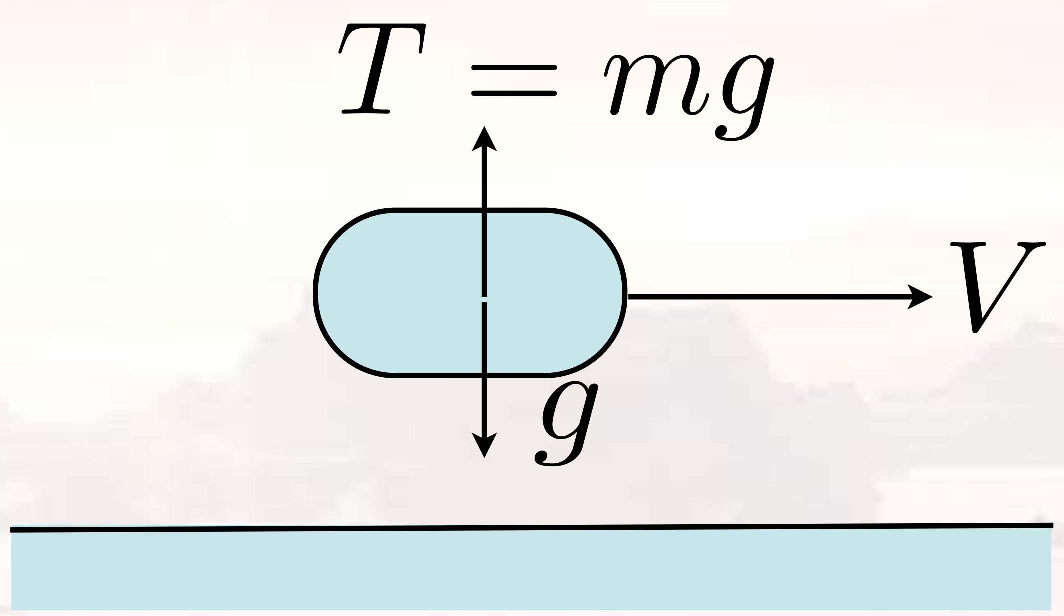
$$\gamma_{opt} = \frac{\pi}{2} = 45^o \qquad d_{max} = \frac{V^2}{g}$$

$$V = \sqrt{gd} \qquad \Delta V_{total} = 2V = 2\sqrt{gd}$$

$$h_{max} = V_v \frac{V_v}{g} - \frac{1}{2} g \left(\frac{V_v}{g}\right)^2 \qquad V_v = \frac{V}{\sqrt{2}}$$

$$h_{max} = \frac{V^2}{4g} = \frac{\sqrt{gd}^2}{4g} = \frac{d}{4}$$

Propulsive Gliding (Airless Flat Planet)



Assume horizontal velocity is V

$$\Delta V_h = 2V$$

(includes acceleration and deceleration)

$$t_{flt} = d/V$$

$$\Delta V_v = g t_{flt} = \frac{gd}{V}$$

Total ΔV becomes

$$\Delta V_{total} = \Delta V_v + \Delta V_h = 2V + \frac{gd}{V}$$

Propulsive Gliding (Airless Flat Planet)

Want to choose V to minimize

$$\frac{\partial}{\partial V}\left(2V + \frac{gd}{V}\right) = 0 \qquad 2 - \frac{gd}{V^2} = 0$$

$$V_{opt} = \sqrt{\frac{gd}{2}}$$

$$\Delta V_{total} = 2\sqrt{\frac{gd}{2}} + gd\sqrt{\frac{2}{gd}} = \boxed{2\sqrt{2}\sqrt{gd}}$$

Nondimensional Forms

$$\text{Define } \nu \equiv \frac{V}{\sqrt{dg}} \qquad \rho \equiv \frac{d}{r} \qquad \eta \equiv \frac{h_{max}}{d}$$

$$\nu_{flat\ glide} = 2\sqrt{2}$$

$$\nu_{flat\ hop} = 2 \qquad \eta = \frac{1}{4}$$

$$\nu_{spherical\ glide} = 2\sqrt{2-\rho} \qquad (0 \leq \rho \leq 1)$$

Multiple Hops

- Assume n hops between origin and destination
- At each intermediate "touchdown", v_v has to be reversed

$$\Delta V_{total} = 2V + 2(n-1)V_v$$

$$t_{peak} = \frac{V_v}{g} \qquad t_{total} = 2nt_{peak} = 2n\frac{V_v}{g}$$

$$d = V_h t_{total} = \frac{2n}{g}V_h V_v \qquad V_v = \sqrt{2gh_{max}} \qquad \nu_v = \sqrt{\frac{2\eta}{n}}$$

$$\nu \equiv \frac{V}{\sqrt{dg}} \qquad \eta \equiv \frac{h_{max}}{d/n} \qquad V_h = \frac{dg}{2nV_v} \qquad \nu_h = \frac{1}{2}\sqrt{\frac{1}{2n\eta}}$$

Multiple Hop Analysis

$$\Delta\nu = 2\nu + 2(n-1)\nu_v$$

$$\Delta\nu = 2\sqrt{\nu_v^2 + \nu_h^2} + 2(n-1)\nu_v$$

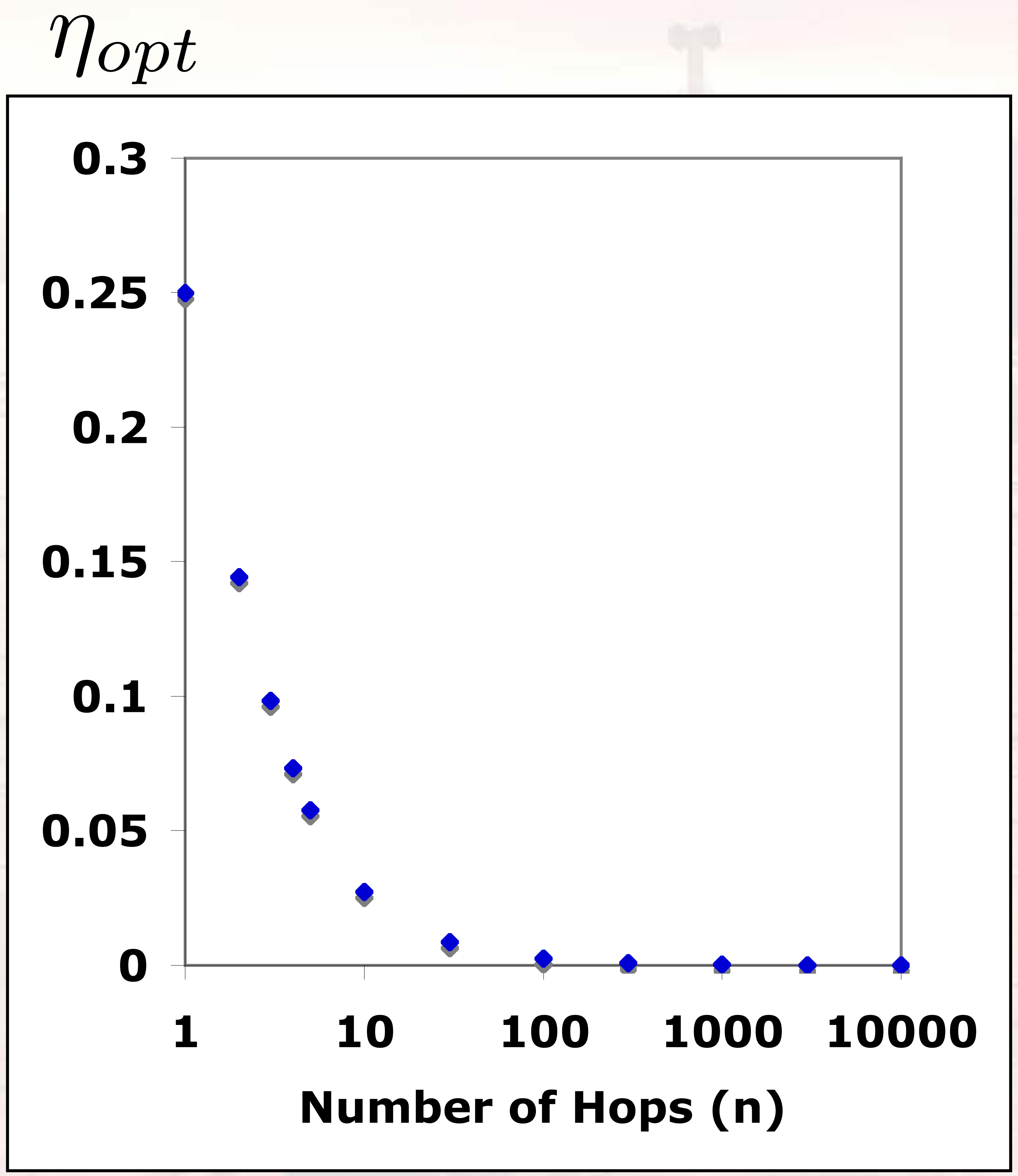
$$\Delta\nu = 2\sqrt{\frac{2\eta}{n} + \frac{1}{8n\eta}} + 2(n-1)\sqrt{\frac{2\eta}{n}}$$

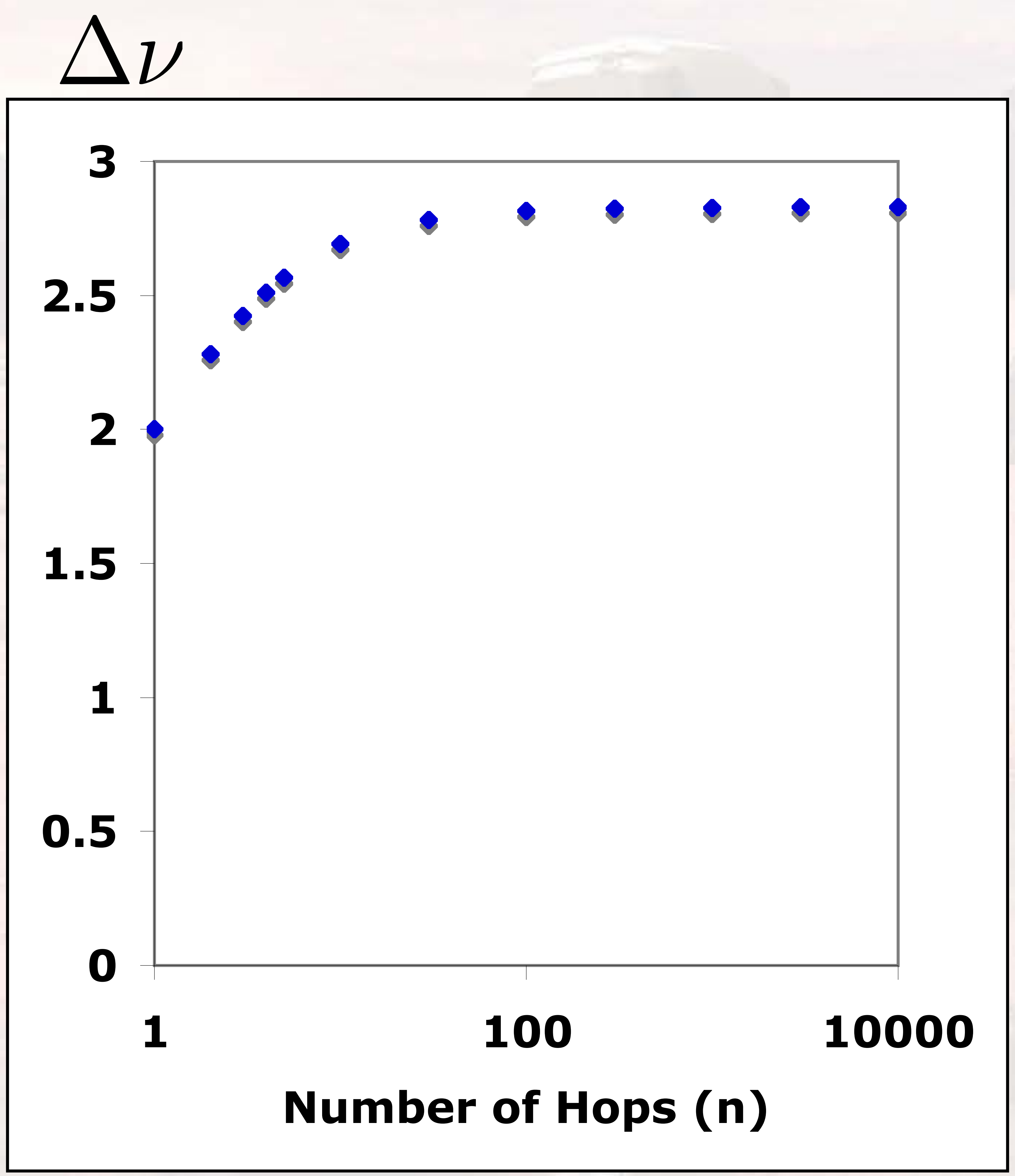
$$\frac{\partial\Delta\nu}{\partial\eta} = \left[\frac{1}{\sqrt{\frac{2\eta}{n} + \frac{1}{8n\eta}}}\left(\frac{2}{n} - \frac{1}{8n\eta^2}\right)\right] + (n-1)\sqrt{\frac{2}{n\eta}} = 0$$

Analytically messy, but note that for $n = 1 \Rightarrow \eta_{opt} = \frac{1}{4}$

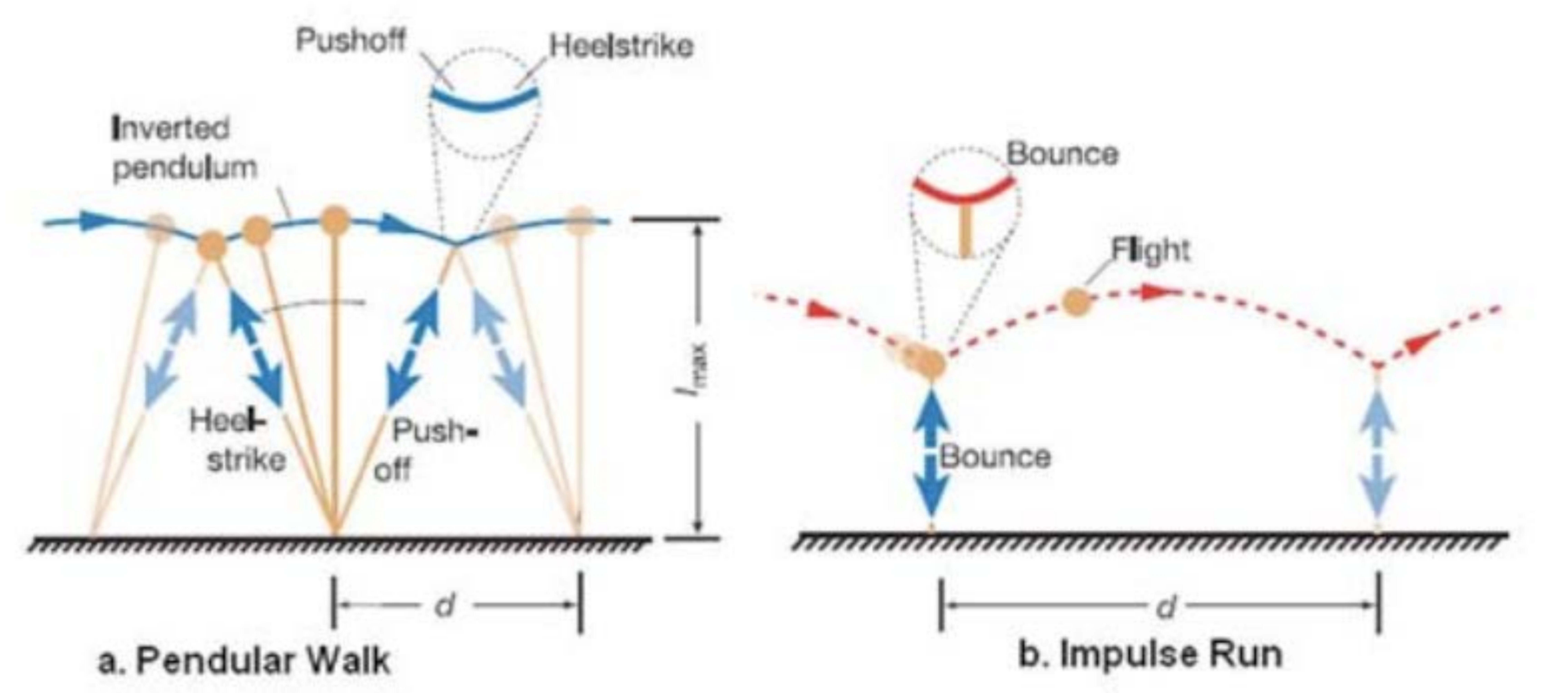
(In general, solve numerically)

Optimal Solutions for Multiple Hops





Walking and Running Gaits



from Rader, Newman, and Carr, *Loping: A Strategy for Reduced Gravity Human Locomotion?* ICES 2007-01-3134, International Conference on Environmental Systems, Chicago, IL, July 2007

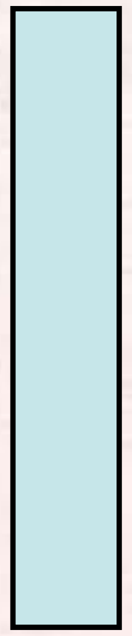
Implications of Pendulum Motion

- Basic period of a pendulum

$$P \approx 2\pi\sqrt{\frac{L}{g}}$$

- Inertias of point and distributed masses

$$I = mL^2$$



$$I = \frac{1}{3}mL^2$$

- For 0.75 m leg length, $P_{walking} \approx 1.0 \text{ sec (on Earth)}$

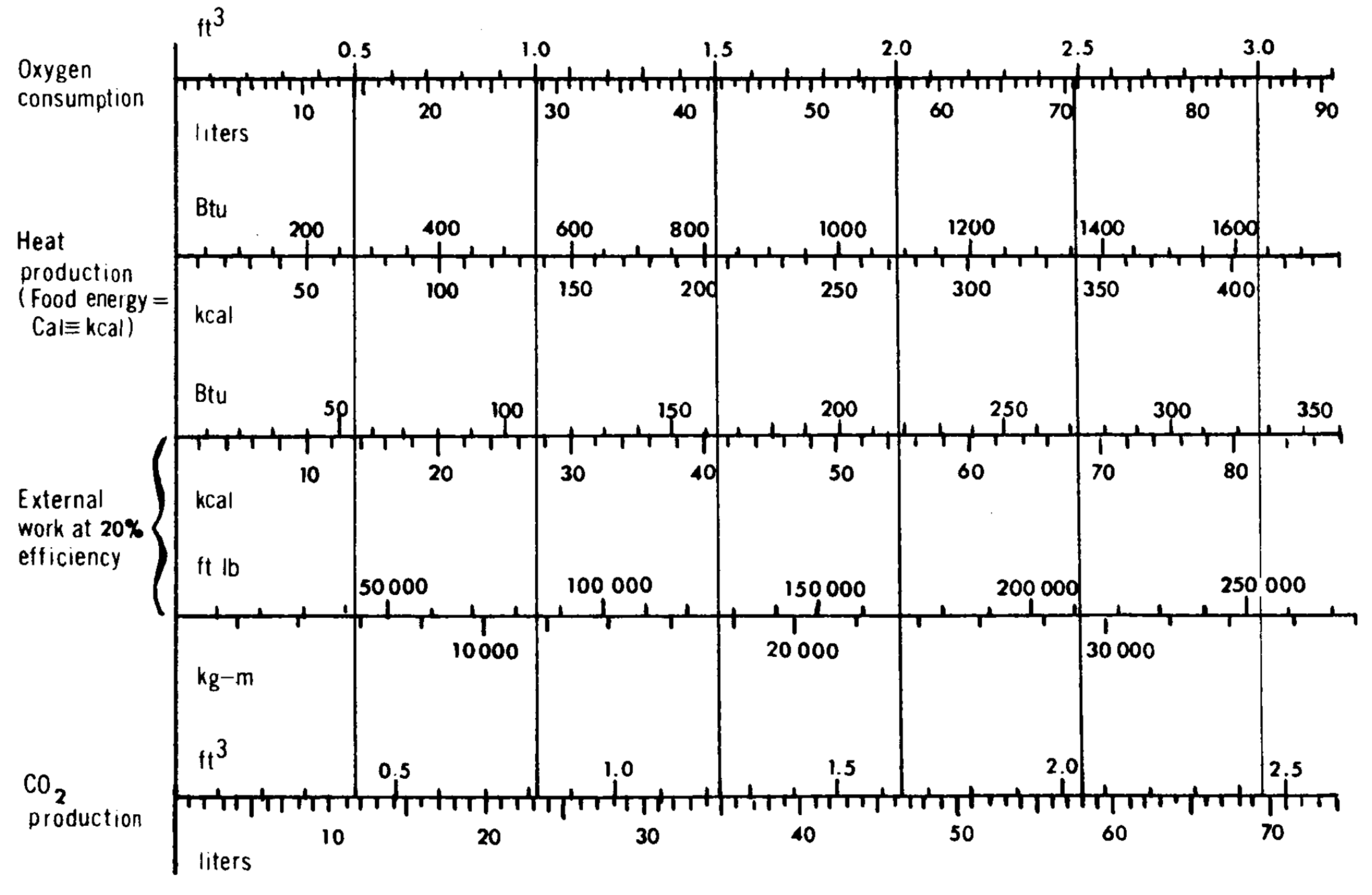
Walking Froude Number

- Froude number is ratio between inertial and gravitational forces
- Primary application is boat speed (transition between displacement and planing motion)
- Walking Froude number

$$Fr = \frac{V^2}{gL} = \frac{a_{centripetal}}{g}$$

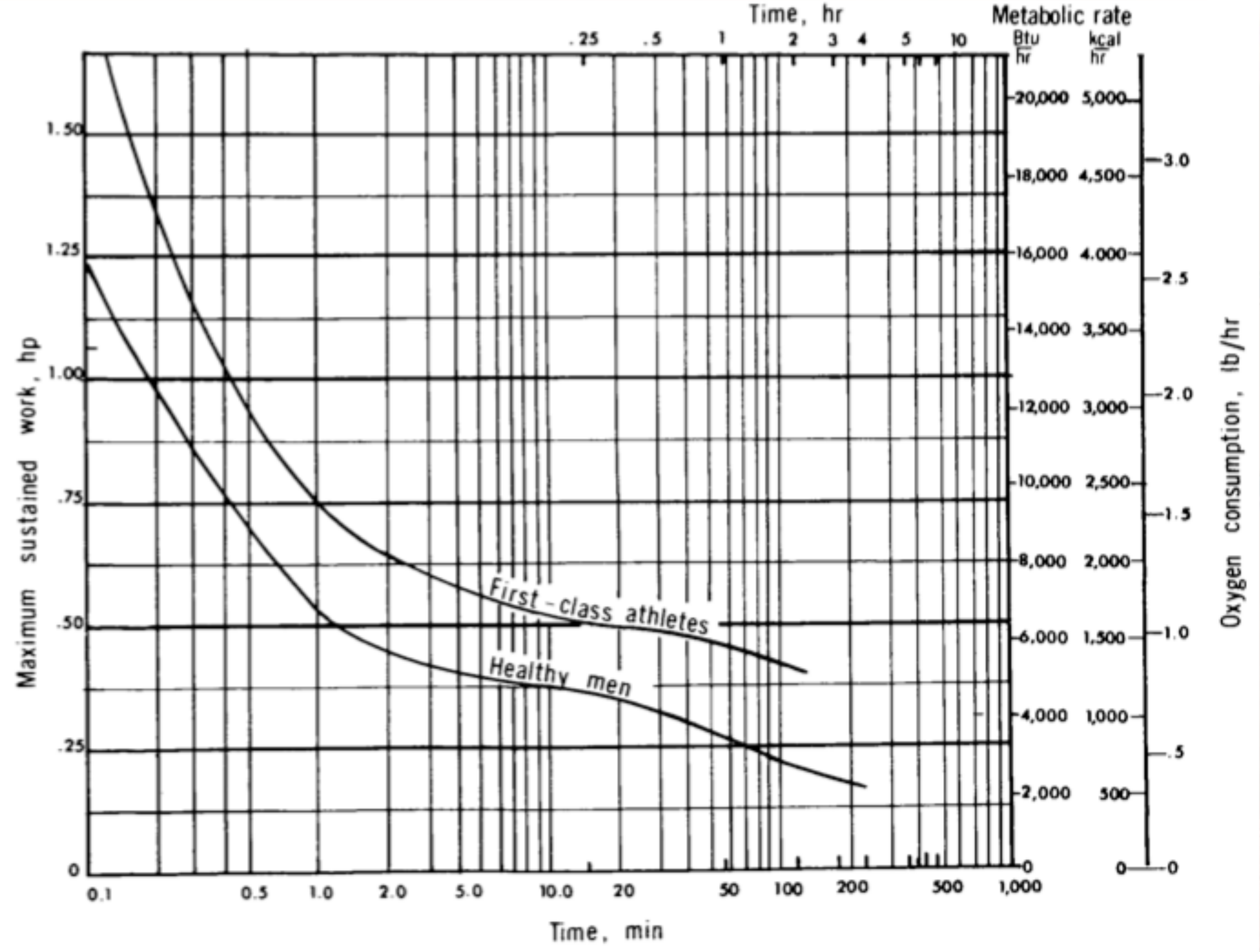
- Feet leave the ground at Fr=1
- Walk-run transition typically occurs ~Fr=0.5

Metabolic Costs of Physical Exertion



from Roth, *Bioenergetics of Space Suits for Lunar Exploration*, NASA SP-84, 1966

Maximum Sustained Work Output



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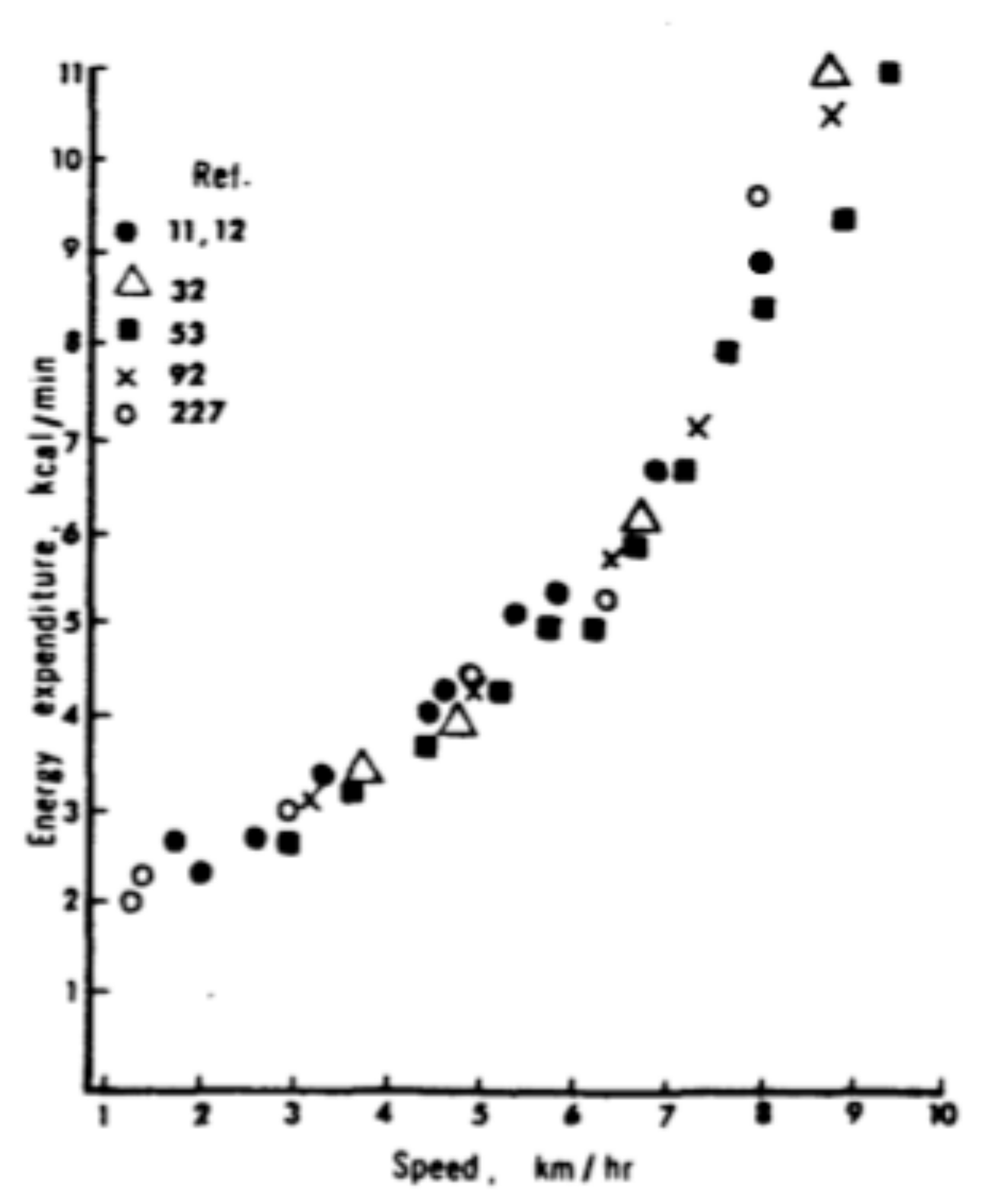
Energy Expenditure in Walking



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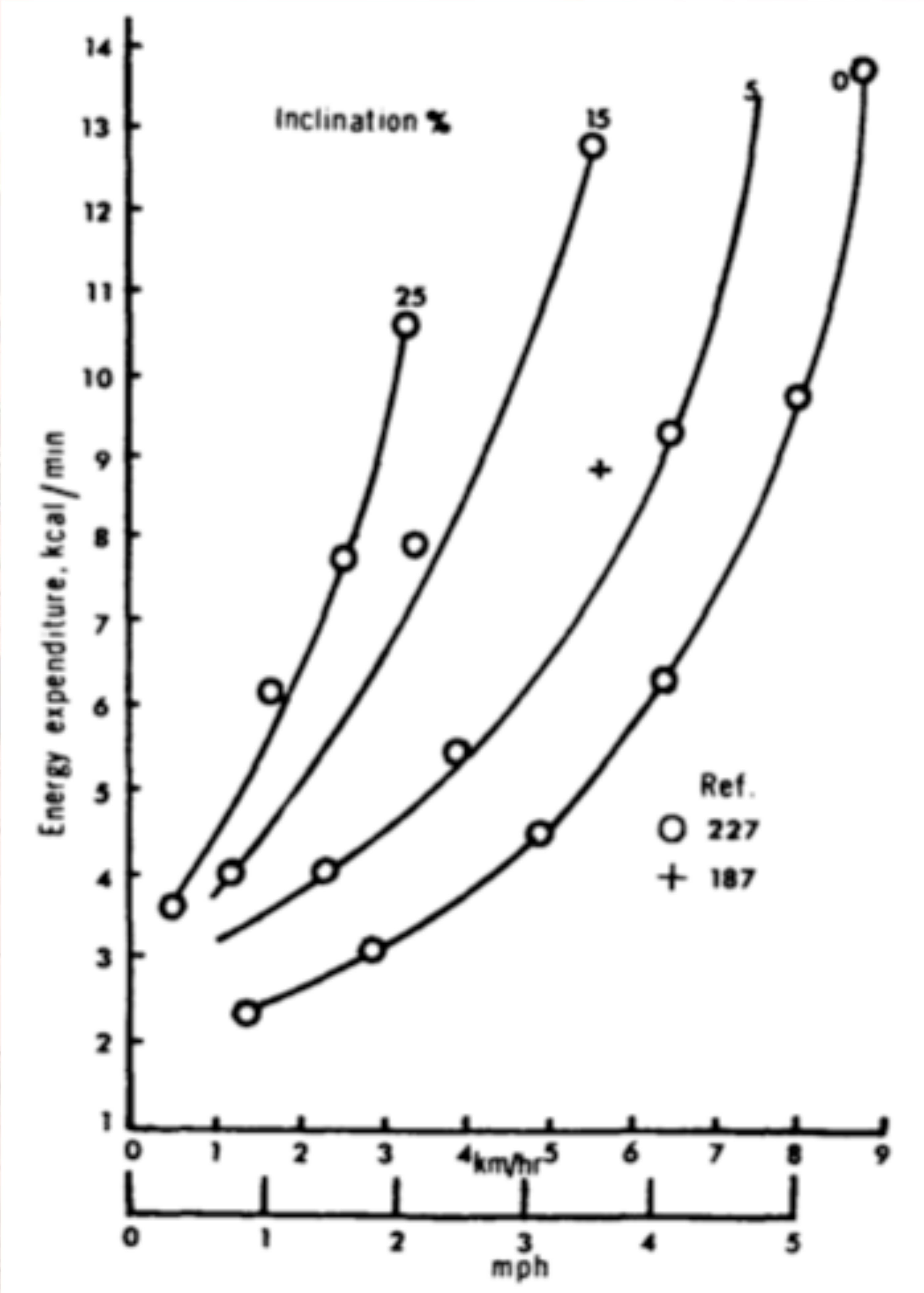
O_2 Requirement to Walk and Run



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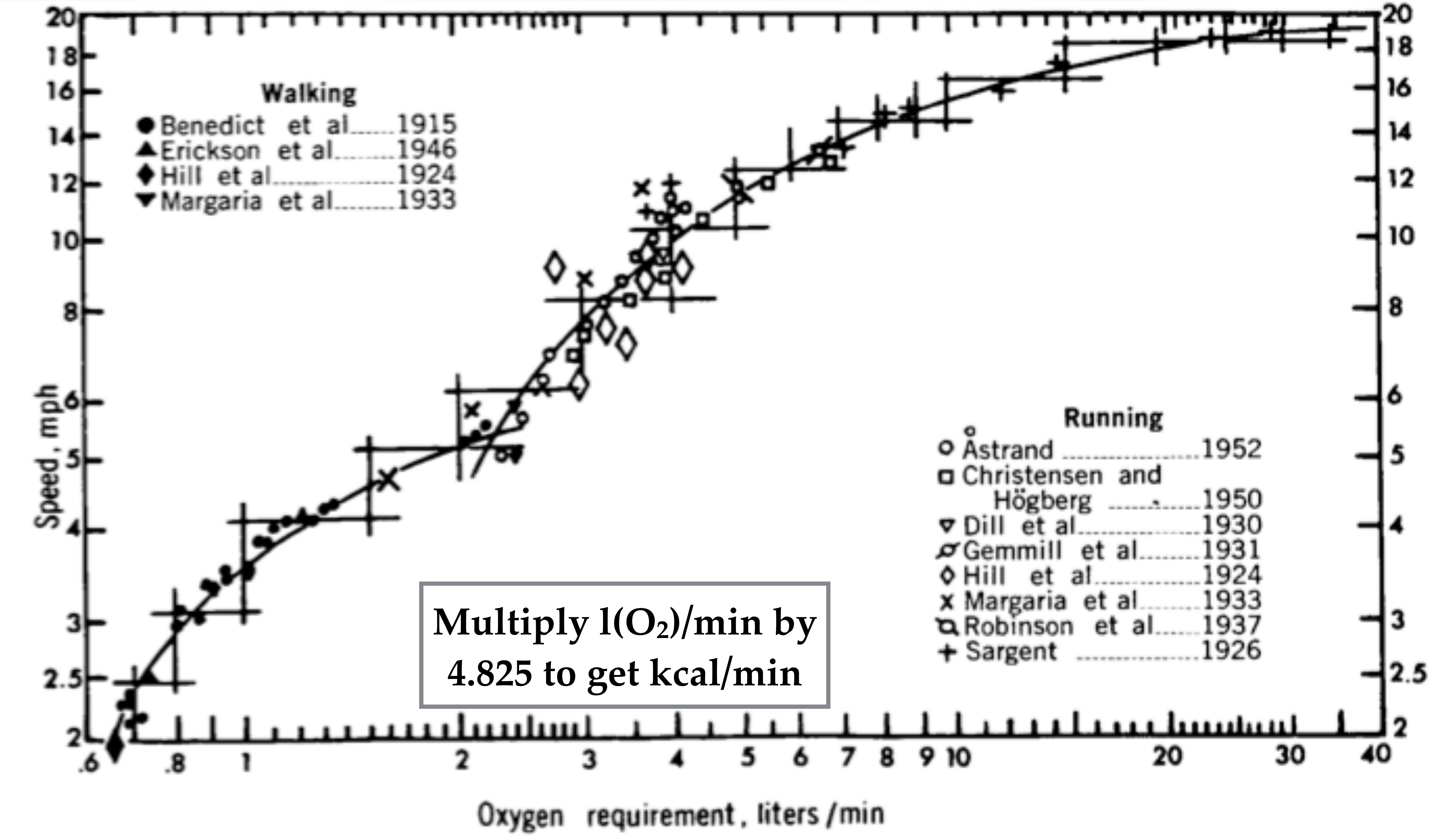
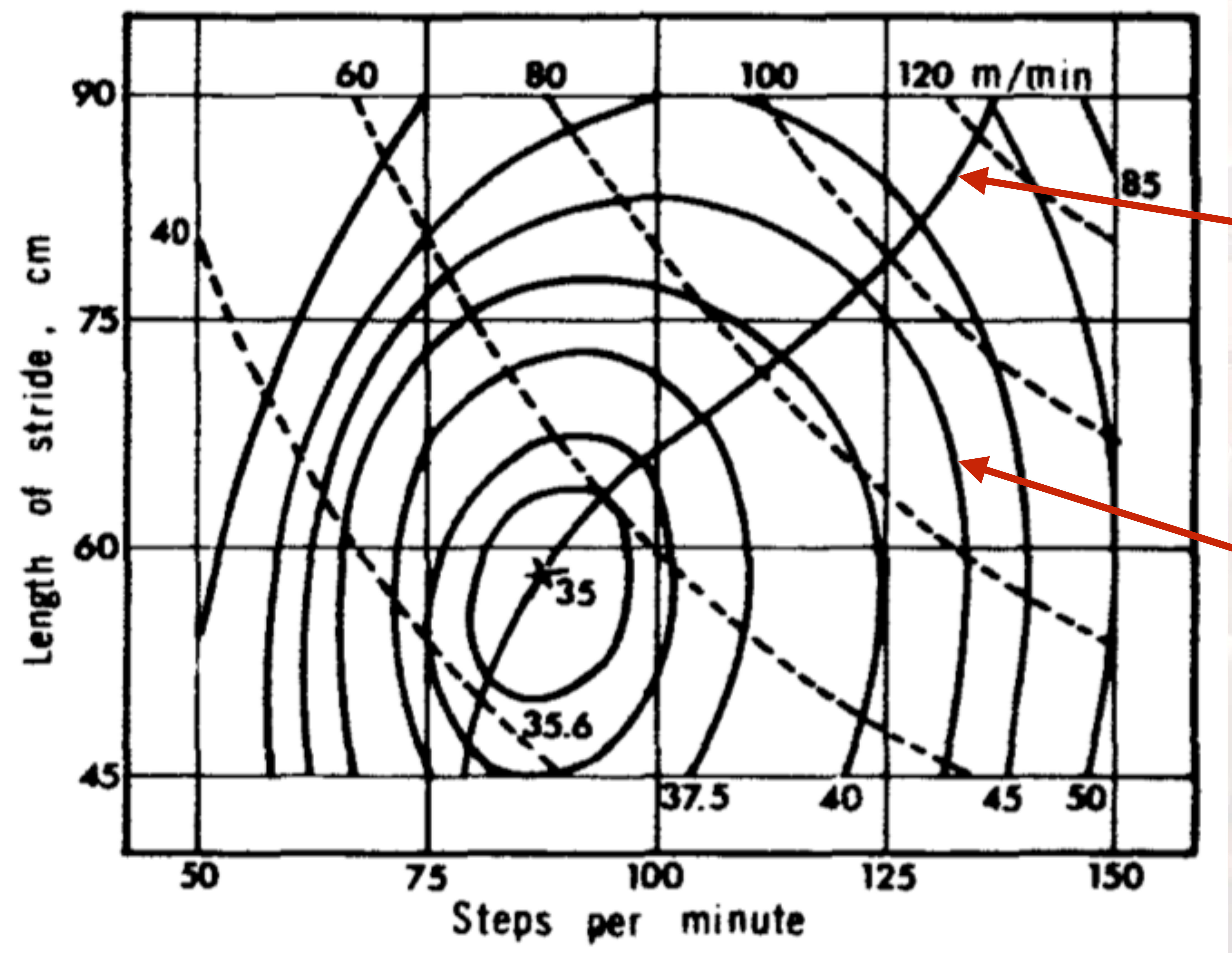
O_2 Requirement to Walk and Run



Multiply $l(O_2)$/min by 4.825 to get kcal/min

from Roth, *Bioenergetics of Space Suits for Lunar Exploration*, NASA SP-84, 1966

Effect of Stride and Cadence

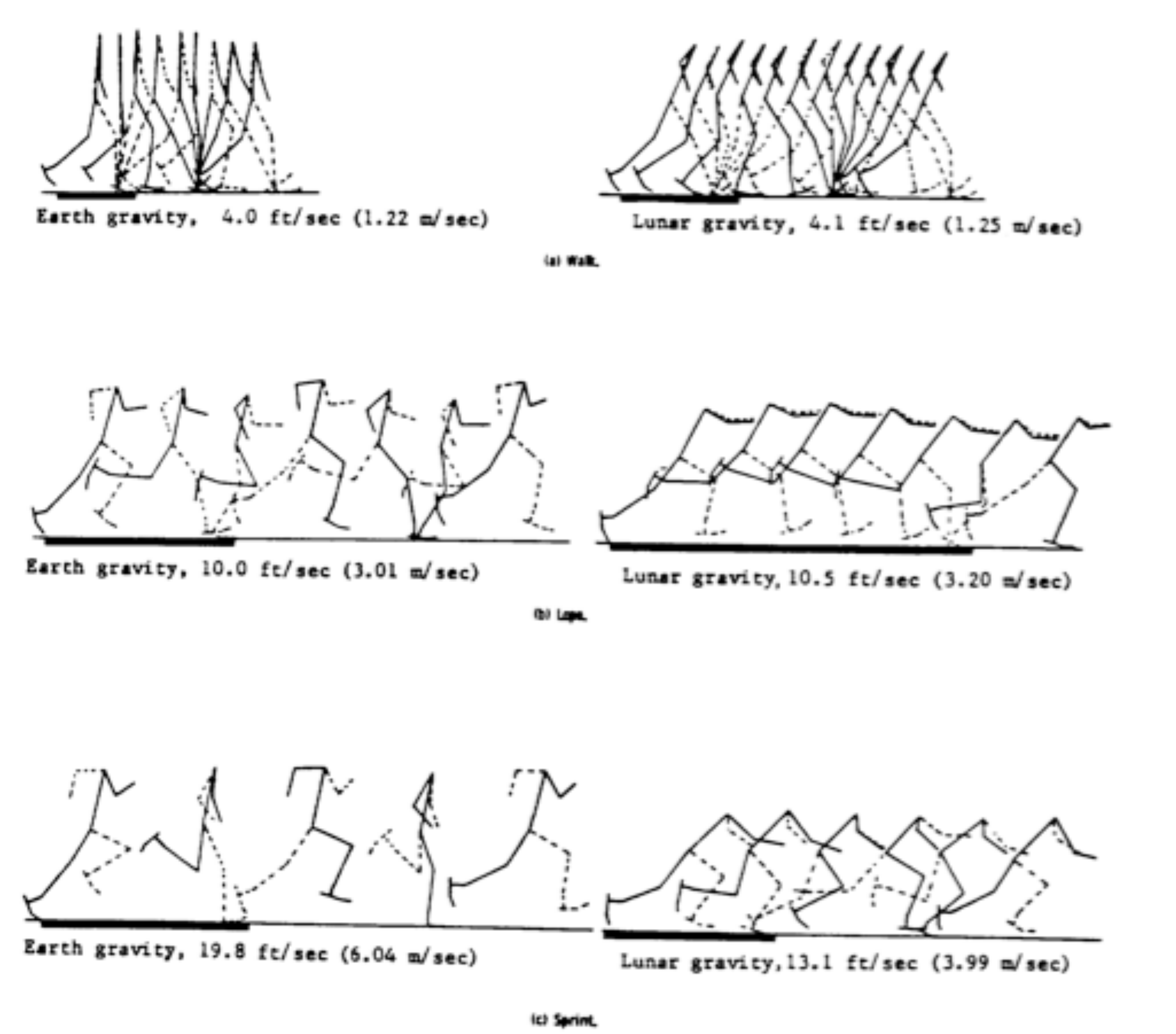


Optimum combination of cadence and stride length

Lines of constant caloric consumption (kcal/min)

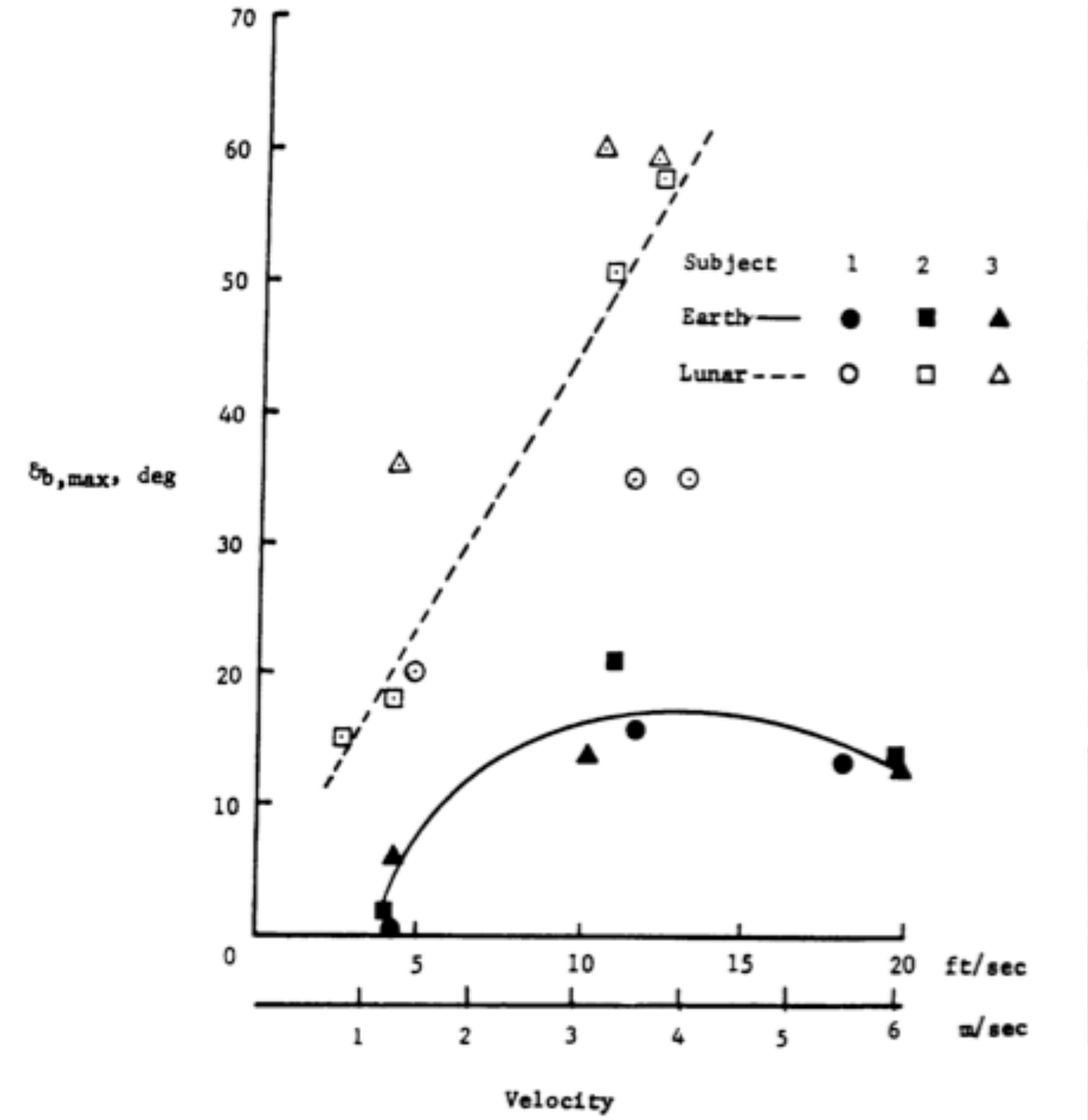
from Roth, *Bioenergetics of Space Suits for Lunar Exploration*, NASA SP-84, 1966

Body Inclination in Variable Gravity



from Partial Gravity Habitat Study, Sasakawa International Center for Space Architecture, University of Houston, 1989

Body Inclination in Variable Gravity



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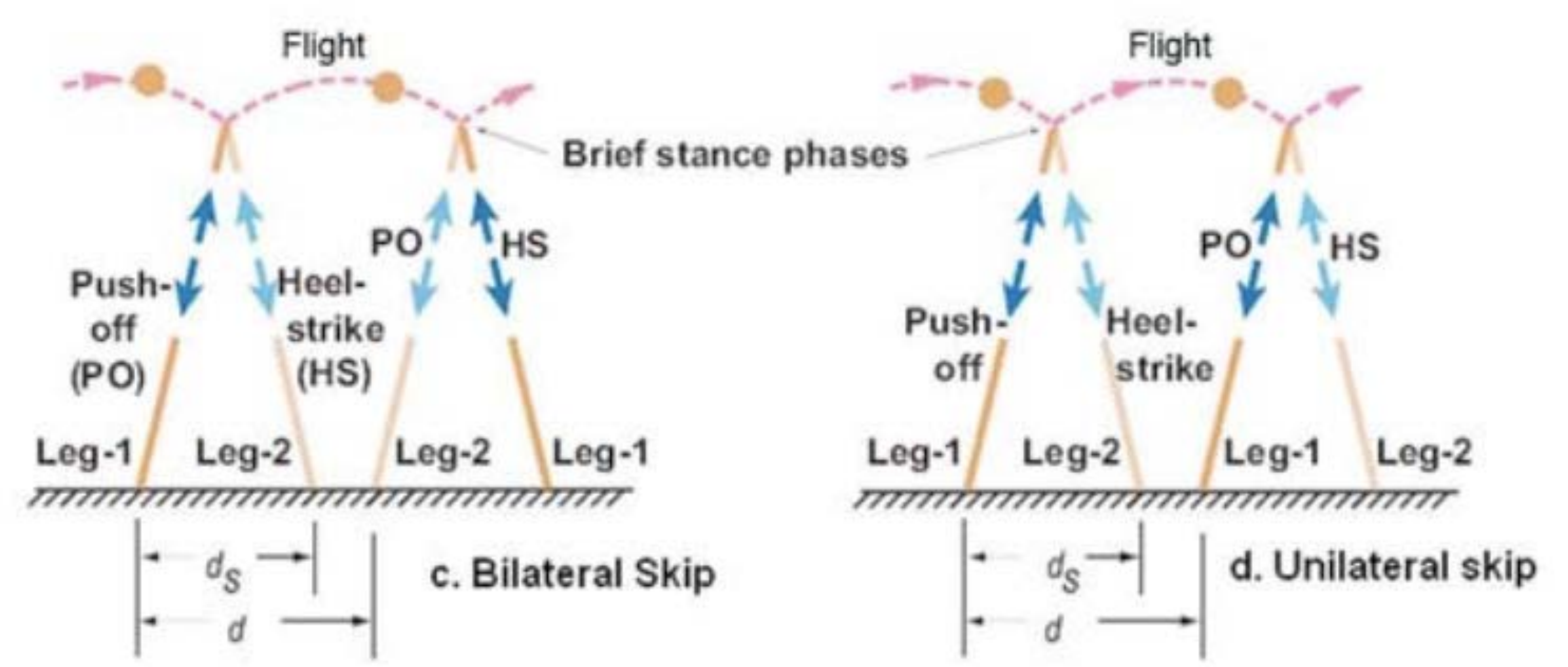
Skipping and Loping Gaits



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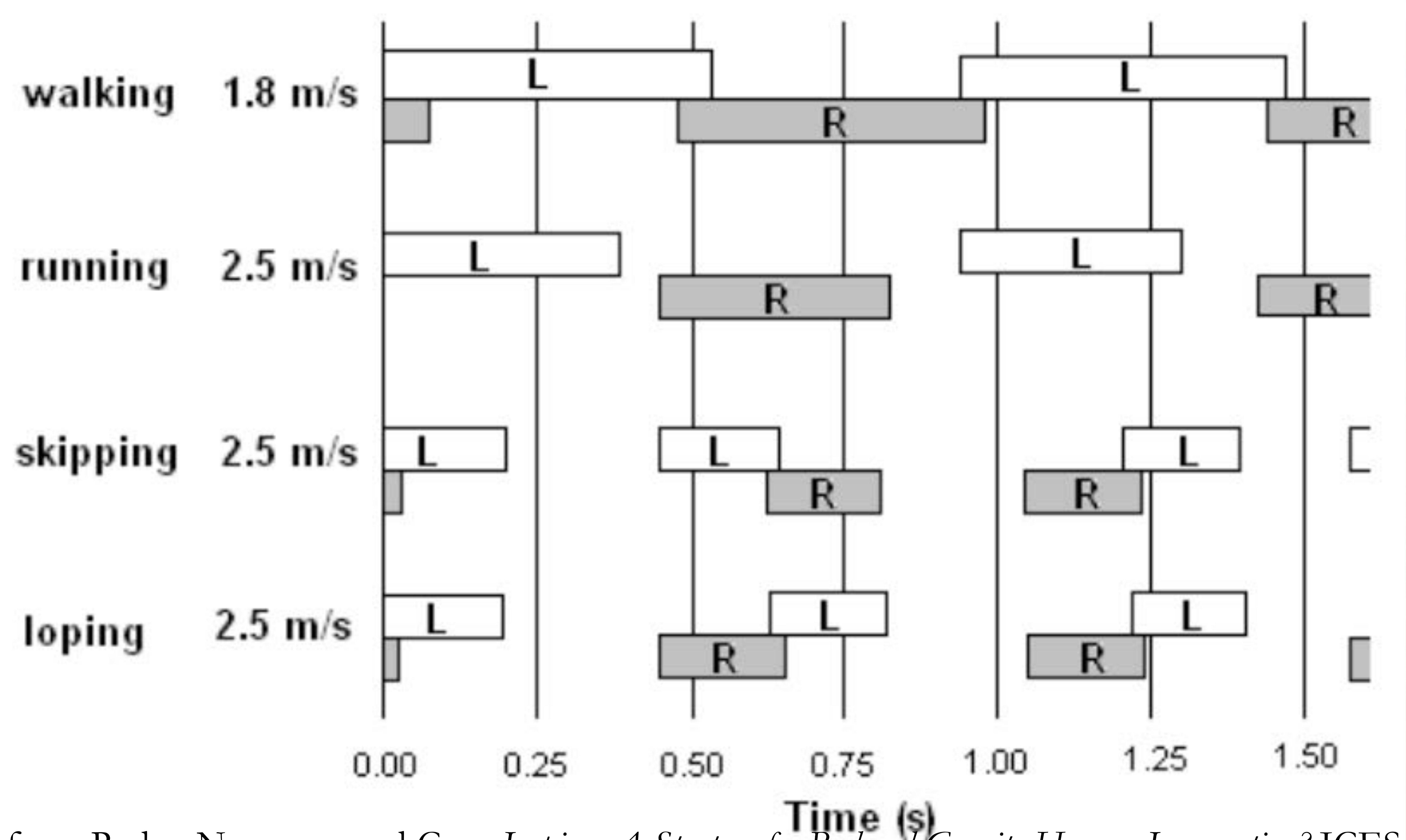
Gait Footfalls



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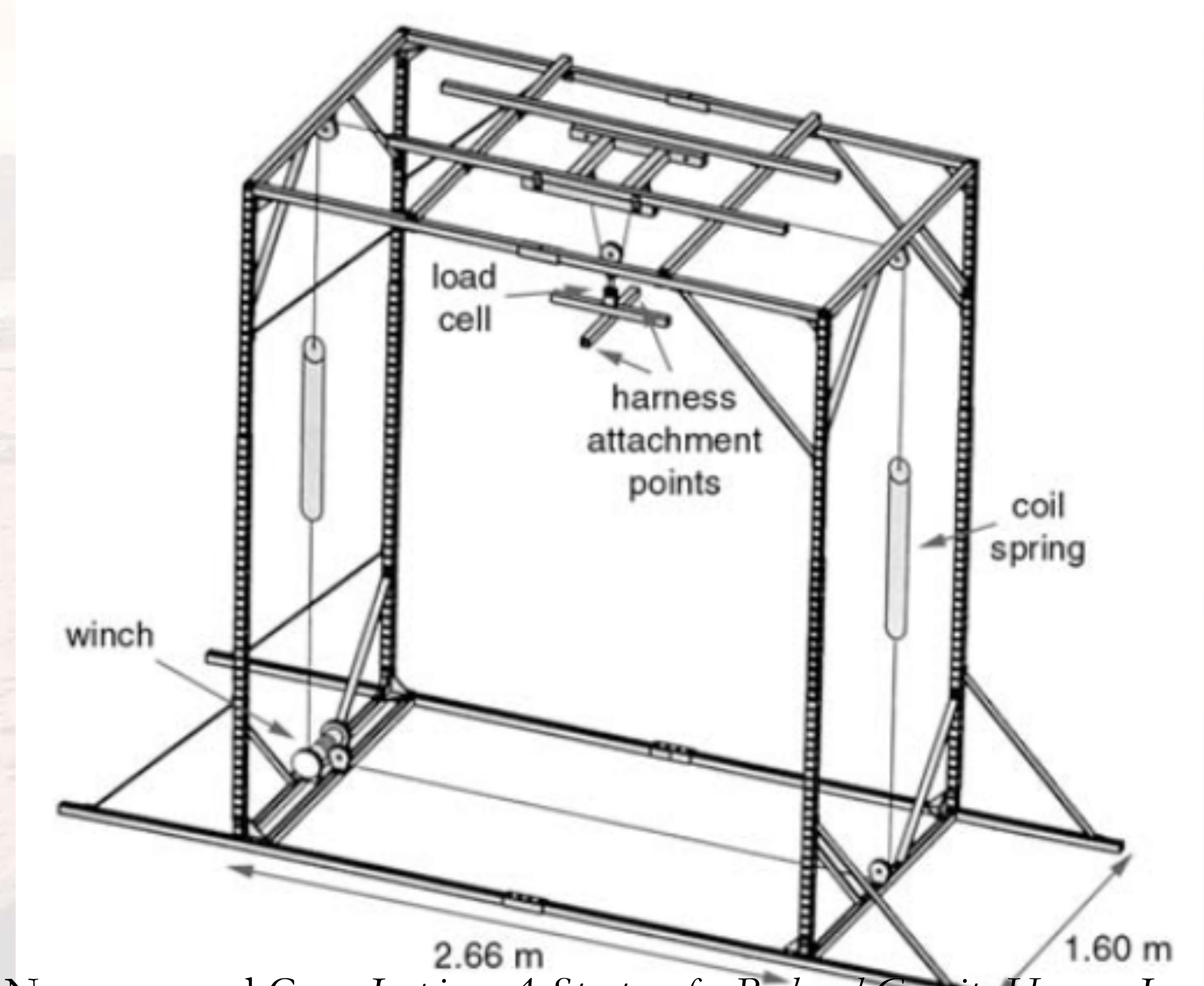
MIT Gravity Offset System



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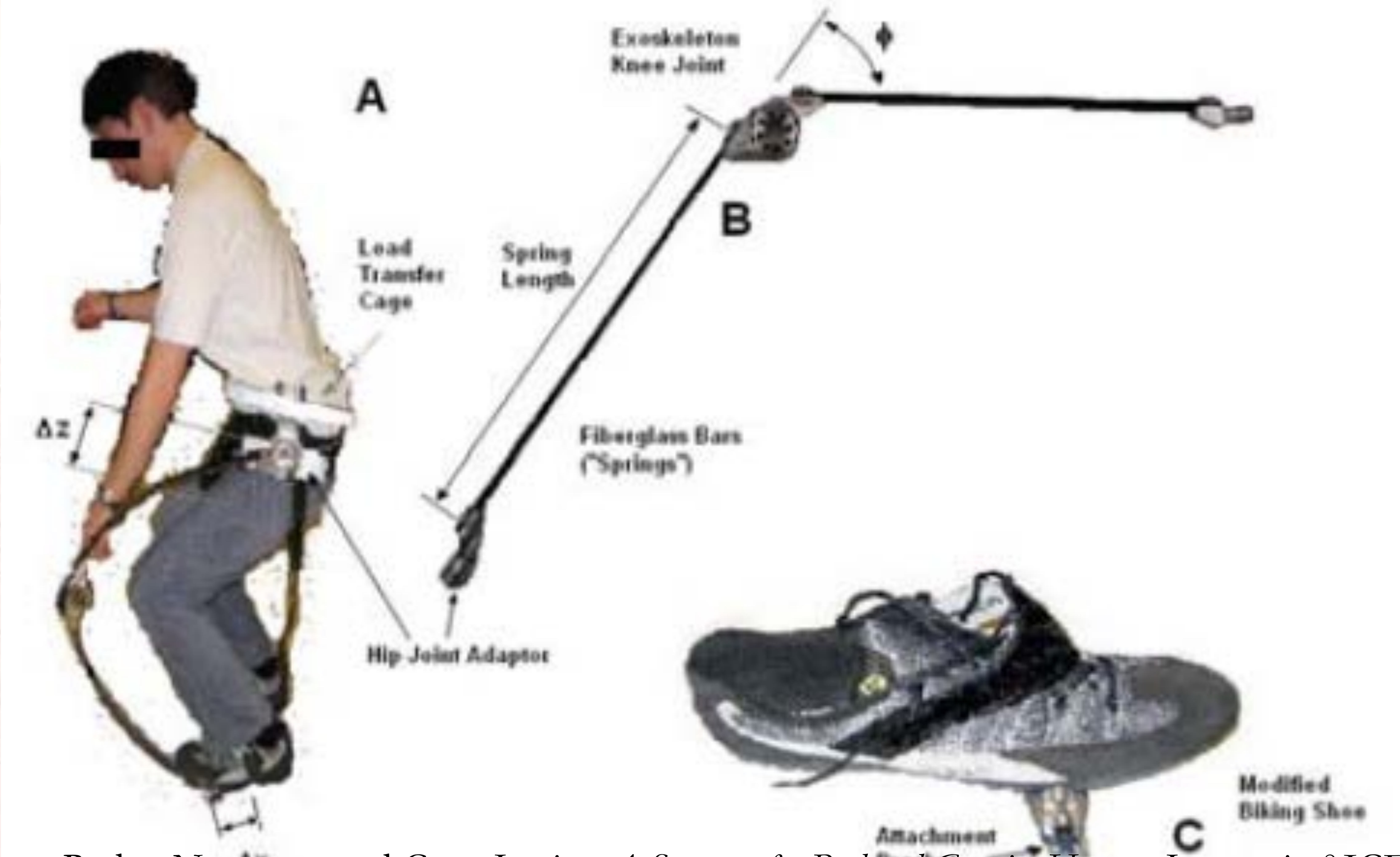
MIT Exoskeletal Suit Joint Simulator



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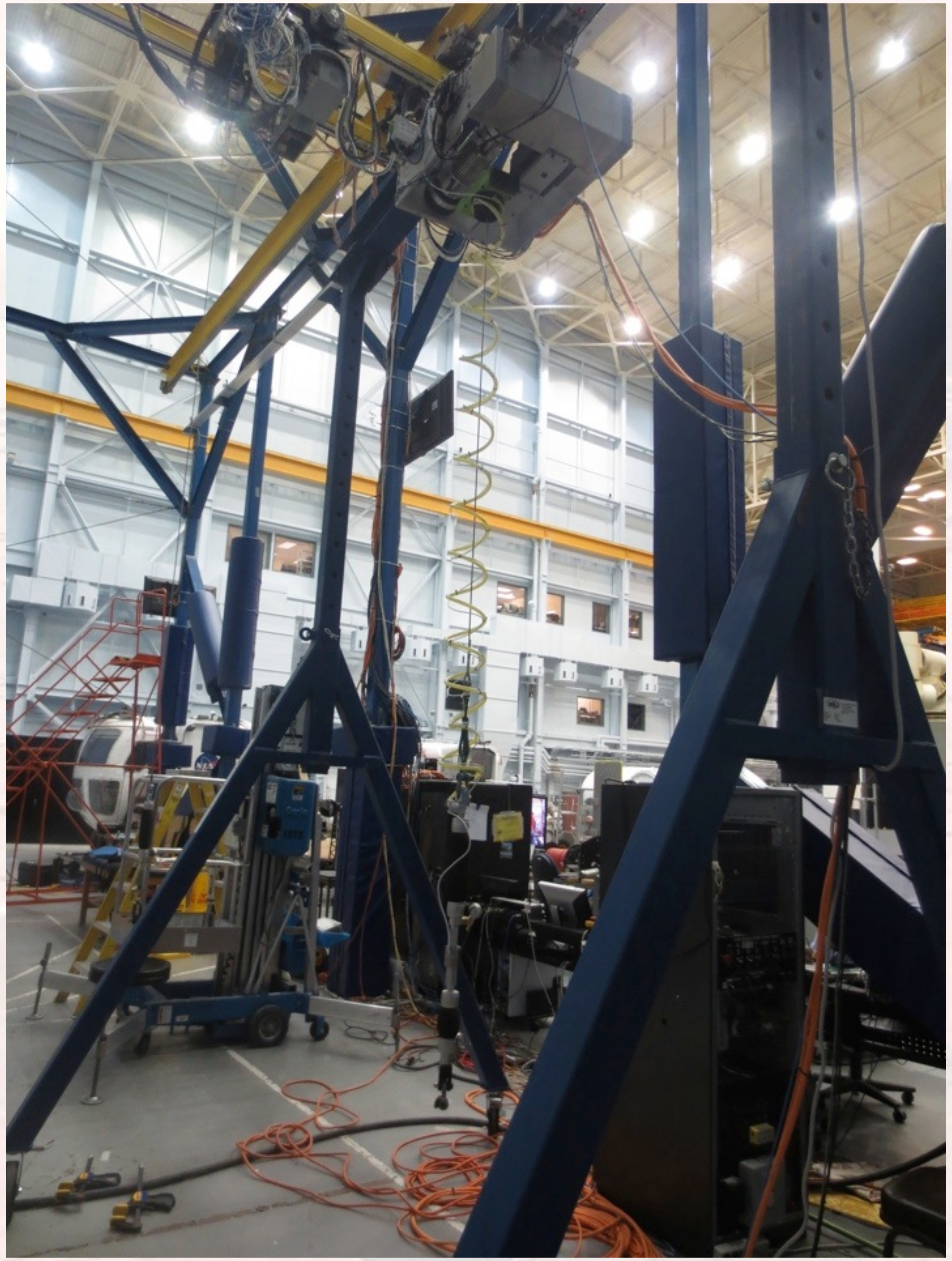
JSC Walkback Tests (2006-2007)

- Testing to verify metabolic cost of 10 km walkback from failed rover in lunar gravity
- Extra-large treadmill
- Pogo (pneumatic suspension) gravity offset device
- Mk. III suit
- Vicon motion tracking system
- Six test subjects (astronauts)
- Measured VO2, RPE, MCH

JSC ARGOS Gravity Offset System

ARGOS Suspension and Tracks

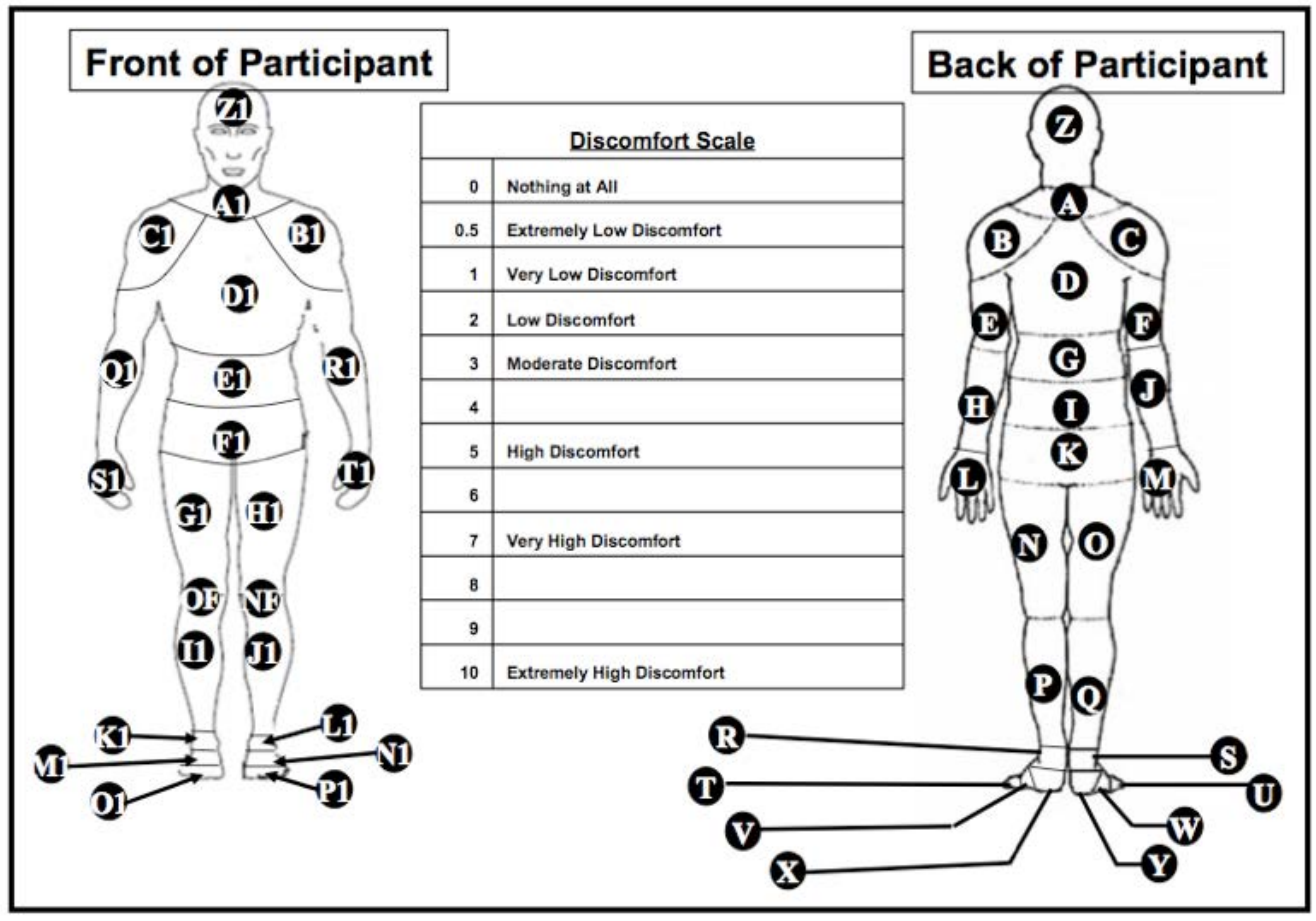


ARGOS Suspension System

Borg Rating of Perceived Exertion (RPE)

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Corlett & Bishop Discomfort Scale



Speeds Used for Testing

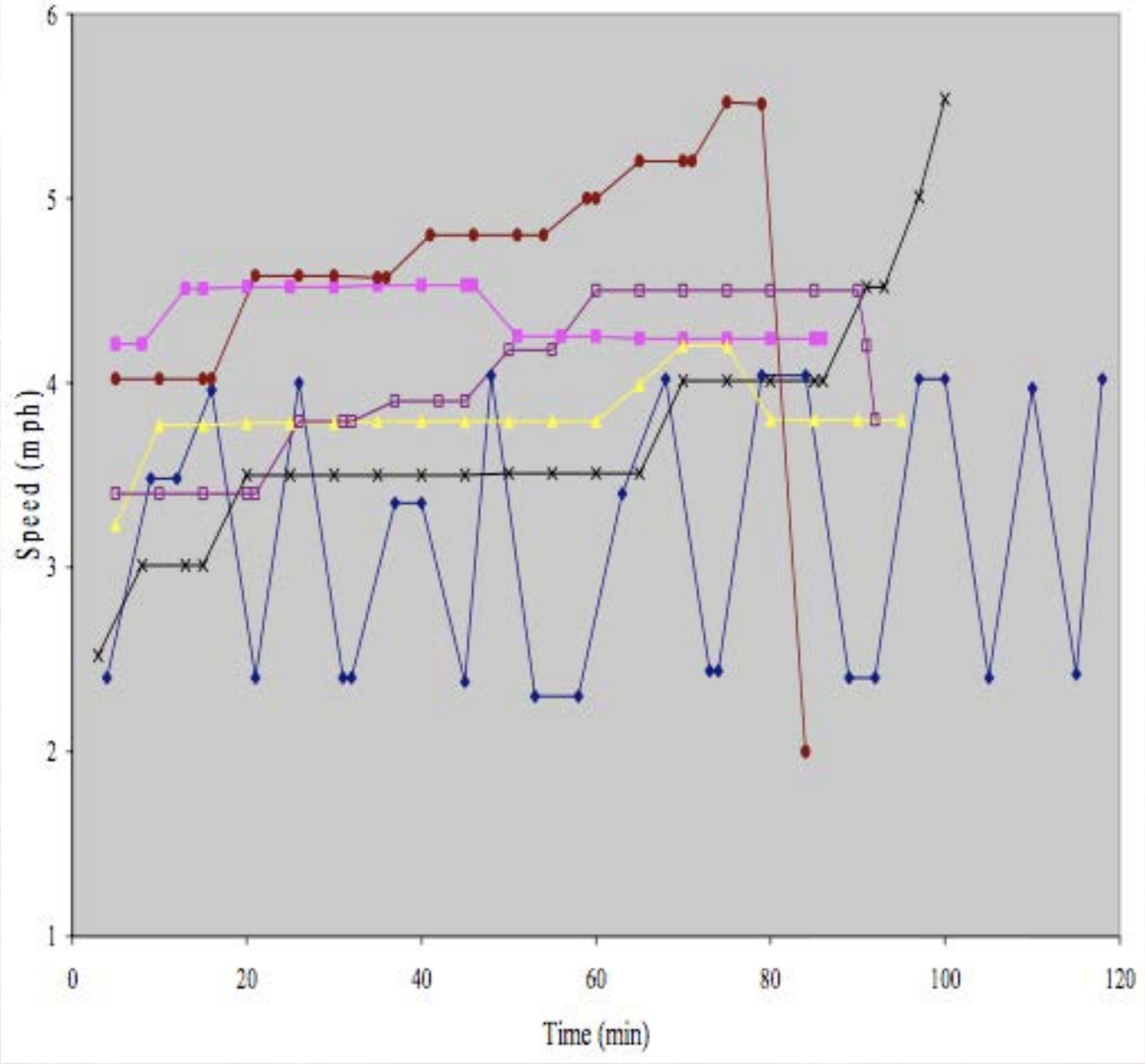
Speeds Used for the Energy-Velocity Tests:		
Stage	Speed	Comments
1	X minus 1.1 mph	Subtract 0.3 mph per stage; need smaller increments for walking
2	X minus 0.8 mph	
3	X minus 0.5 mph	Subtract 0.5 mph to assure walking out of transition zone
PTS = X		No data collected in transition zone
4	X plus 0.5 mph	Add 0.5 mph to assure running out of transition zone
5	X plus 1.5 mph	Add 1.0 mph to distinguish metabolic/biomechanical differences at running speeds
6	X plus 2.5 mph	

Shirt-Sleeve Suspension

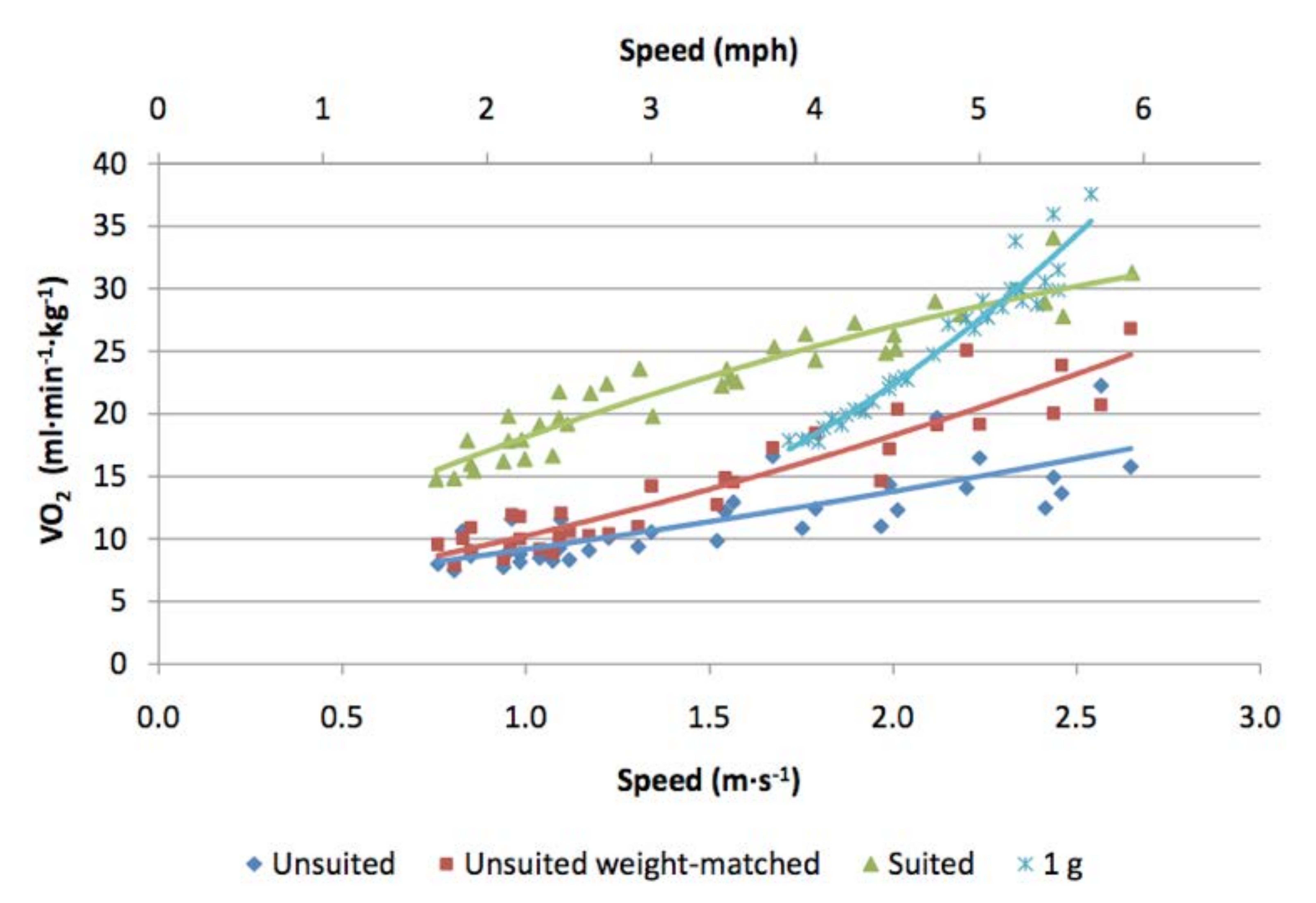
Suited Partial-Gravity Suspension

Details of Gimbal Mount to Pogo System

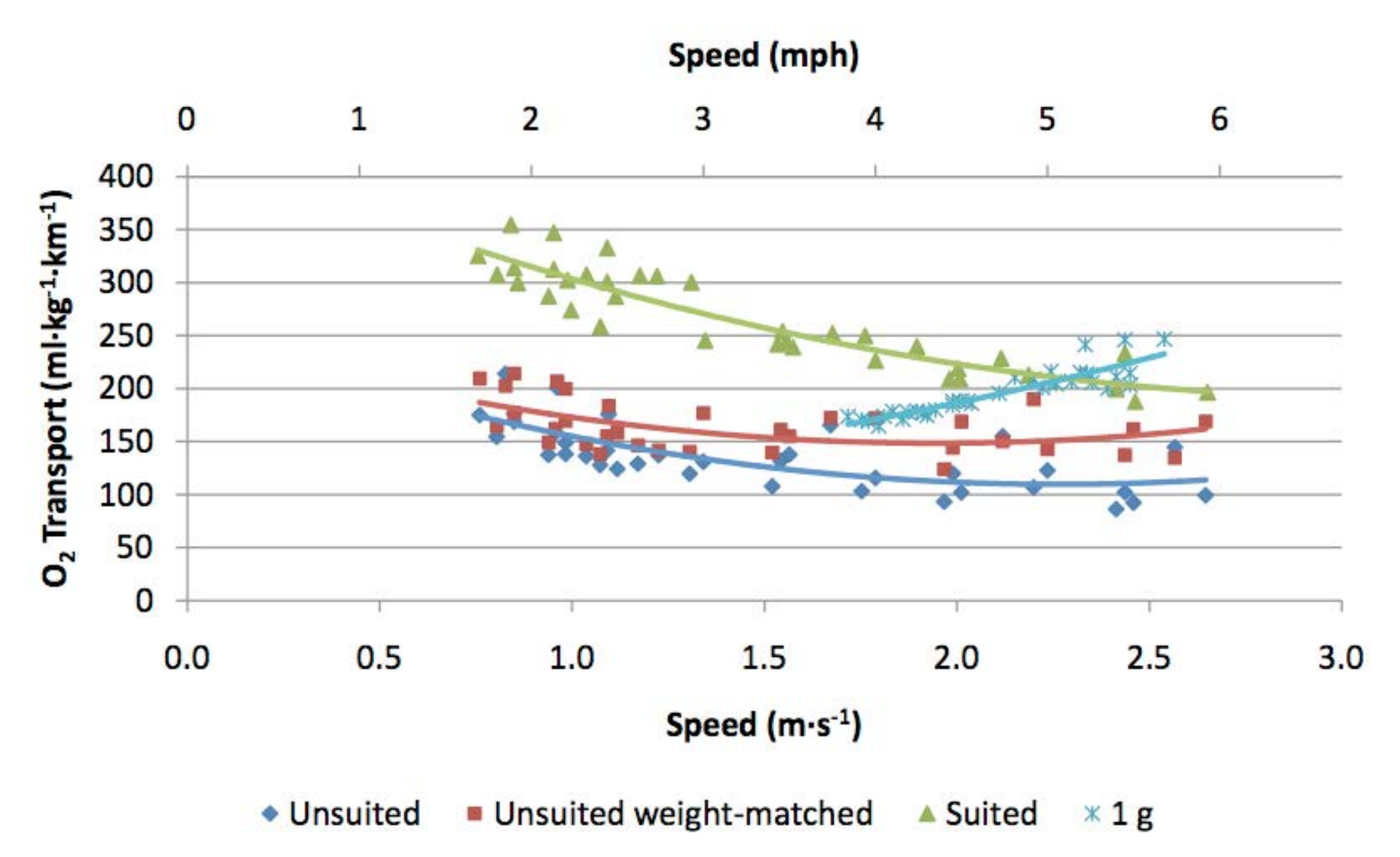
Test Subject Performing 10 km Traverse



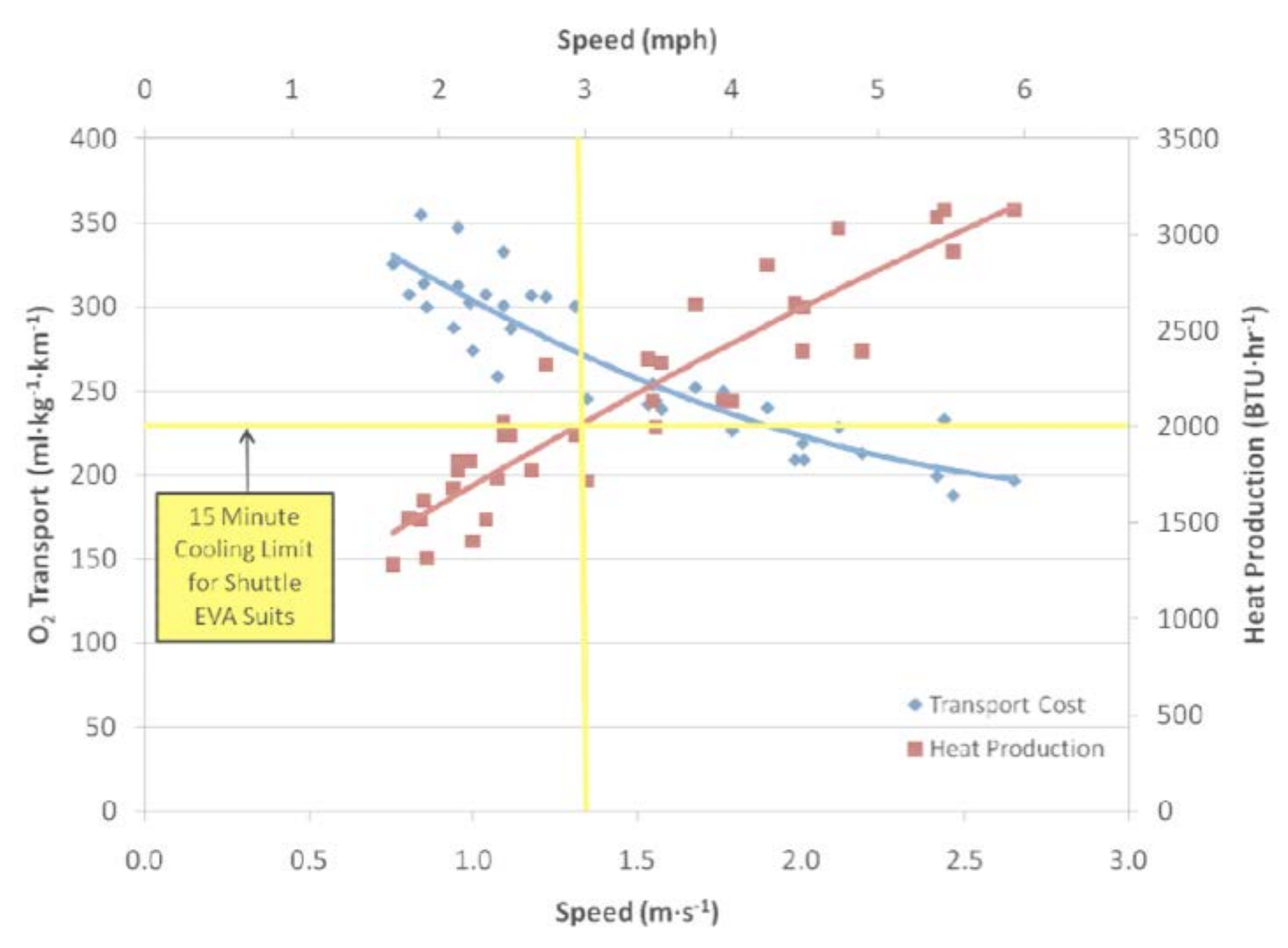
Metabolic Costs of Lunar Locomotion



O2 Transport Cost of Lunar Locomotion



Cooling and Energy Use in Lunar Run



References for This Lecture

- Gernhardt, Norcross, and Vos, *Integrated Suit Test 1 - A Study to Evaluate Effects of Suit Weight, Pressure, and Kinematics on Human Performance During Lunar Ambulation* ICES 2008-01-1951, International Conference on Environmental Systems, San Francisco, CA, July 2008
- Vos, Gernhardt, and Lee, *The Walkback Test: A Study to Evaluate Suit and Life Support System Performance Requirements for a 10 Kilometer Lunar Traverse in a Planetary Suit* ICES 2007-01-3133, International Conference on Environmental Systems, Chicago, IL, July 2007
- Rader, Newman, and Carr, *Loping: A Strategy for Reduced Gravity Human Locomotion?* ICES 2007-01-3134, International Conference on Environmental Systems, Chicago, IL, July 2007