Human Walking Energetics
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Outline
Metabolic cost
Mechanical work
Efficiency
Determinants of walking’s metabolic cost.

Variables of Interest

Work
change in energy, force applied over a distance
(Joules, kilocalories, Watt-hours, VO₂)

Power
work per unit time
(Watts, kcal/hr, W/kg, VO₂, W/(Mg^{3/2}L^{1/2}))

Cost of transport
work per unit distance
(J/kg/m, J/kg/m/g or W/M/g/v)

Minimizing metabolic cost explains human walking biomechanics

(Atzler and Herbst, 1927; Elftman, 1967)
**Cost of Transport**

![Cost of Transport Diagram](Image)

(Tucker, 1975)

**Metabolism**

**Functional Definition**
Sum of all transformations of energy and matter that happen within an organism

**Operational Definition**
Rate of heat production

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**Basal Metabolic Rate**

5 organs account for 80% of the energy expended in basal conditions by a 70 kg man: Liver (27%; 1.6 kg), Brain (19%; 1.4 kg), Muscle (18%, 30 kg) Kidneys (10%, 0.3 kg), Heart (7%, 0.3 kg).

~10% of the oxygen consumed during BMR is consumed by nonmitochondrial processes, ~20% is consumed by mitochondria to counteract the mitochondrial proton leak, and the remaining ~70% is consumed for mitochondrial ATP production.

At a whole-animal level, ATP production can be divided into ~20%–25% for Na⁺,K⁺-ATPase activity, ~20%–25% for protein synthesis, ~5% for Ca²⁺-ATPase activity, ~7% for gluconeogenesis, ~2% for ureagenesis, ~5% for actinomyosin-ATPase activity, and ~6% for all other ATP-consuming processes.

(Durnin, 1981; Hulbert and Else, 2004)

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**1st law of thermodynamics**

Energy Output (work* + heat) = Energy Input

*If we can estimate work, or we know net work is zero, we can simply measure heat production to determine the bodies chemical energy requirements.
Measuring Metabolic Cost: Direct Calorimetry

(Lavoisier, 1780)  
(Webb et al., 1972)  
(Brooks et al., 2005)

Measuring Metabolic Cost: Indirect Calorimetry

(Zuntz et al., 1906)  
(Atwater and Benedict, 1902)

Measure either heat production or O₂ consumption.

Comparison of direct and indirect calorimeters demonstrate that they are of equivalent accuracy.

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Food, energy and respiratory exchange ratio

**Carbohydrates**

\[
C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + E_1
\]

**Fats**

\[
C_{15}H_{31}COOH + 23O_2 \rightarrow 16CO_2 + 16H_2O + E_2
\]

(Brooks et al., 2005)

<table>
<thead>
<tr>
<th>Energy Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy (kJg)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Lead Acid Gel</td>
</tr>
<tr>
<td>Nickel Cadmium</td>
</tr>
<tr>
<td>Batteries</td>
</tr>
<tr>
<td>Nickel-Metal Hydride</td>
</tr>
<tr>
<td>Zinc-Air</td>
</tr>
<tr>
<td>Gases</td>
</tr>
<tr>
<td>Automobile Gasoline</td>
</tr>
<tr>
<td>Foods</td>
</tr>
<tr>
<td>Fat</td>
</tr>
<tr>
<td>Carbohydrates</td>
</tr>
<tr>
<td>Protein</td>
</tr>
<tr>
<td>Ethanol</td>
</tr>
</tbody>
</table>

*The amount of protein combusted outside the body in greater than first combusted inside the body (see text)\[\frac{0.5}{0.7} \times 100 \% = 28\%\] difference.

(Brooks et al., 2005)

Types of calorimeters

- **Direct**
  - C\(_2\) consumption
  - Carbon and nitrogen balance
- **Indirect**
  - Open circuit
  - Closed circuit

Example data
Typical human metabolic energy expenditures

<table>
<thead>
<tr>
<th>Activity</th>
<th>Kilocal/hr</th>
<th>Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>sleeping</td>
<td>70</td>
<td>81</td>
</tr>
<tr>
<td>lying quietly</td>
<td>80</td>
<td>93</td>
</tr>
<tr>
<td>sitting</td>
<td>100</td>
<td>116</td>
</tr>
<tr>
<td>standing at ease</td>
<td>110</td>
<td>128</td>
</tr>
<tr>
<td>conversation</td>
<td>110</td>
<td>128</td>
</tr>
<tr>
<td>eating meal</td>
<td>110</td>
<td>128</td>
</tr>
<tr>
<td>strolling</td>
<td>140</td>
<td>163</td>
</tr>
<tr>
<td>driving car</td>
<td>140</td>
<td>163</td>
</tr>
<tr>
<td>playing violin or piano</td>
<td>140</td>
<td>163</td>
</tr>
<tr>
<td>housekeeping</td>
<td>150</td>
<td>175</td>
</tr>
<tr>
<td>carpentry</td>
<td>230</td>
<td>268</td>
</tr>
<tr>
<td>hiking, 4 mph</td>
<td>350</td>
<td>407</td>
</tr>
<tr>
<td>swimming</td>
<td>500</td>
<td>582</td>
</tr>
<tr>
<td>mountain climbing</td>
<td>600</td>
<td>698</td>
</tr>
<tr>
<td>long distance run</td>
<td>900</td>
<td>1,048</td>
</tr>
<tr>
<td>sprinting</td>
<td>1,400</td>
<td>1,630</td>
</tr>
</tbody>
</table>

Important assumptions and limitations

- Anaerobic metabolism is negligible
- Negligible contribution of changes in protein metabolism to changes in energy output
- Changes in whole body energy requirements reflect changes in body parts of interest.

Useful metabolic energetics equations

“Brockway Equation”

\[ E = 16.58 \text{ kJ/L} (O_2) + 4.51 \text{ kJ/L} (CO_2) - 5.90 \text{ kJ/g UreaNitrogen} \]

“Adamczyk Equation” - 0.1% error

\[ \dot{E} (\text{Watts}) = \frac{16.477 \dot{V}O_2 + 4.484 \dot{V}CO_2}{60} (\text{ml/min}) \]

Simple equation - 3% error

\[ \dot{E} (\text{Watts}) = \frac{21}{60} \dot{V}O_2 (\text{ml/min}) \]

(Brockway, 1987)

Mechanical Energetics
Combined Limbs Method

(Cavagna, 1975)

Joint Power Method

(Elftman, 1939; Winter, 1990)

Individual Limbs Method

(Donelan, Kram and Kuo, 2002)

Relationship between methods

The multi-body JPM reduces to ILM if we assume the legs are massless, the rest of the body is a point mass located at the hip, and we sum joint powers within a leg.

If we also allow joint powers to sum between legs, all three models are equivalent.

Viewing ILM and CLM in this manner illustrates that it is not the GRF that does work on the body—it can’t as the velocity of its point of force application is zero—but the muscles of the leg. The GRF simply estimates the role of leg muscles to generating a force that acts at the hip on the rest of the body.
Assumptions
Importance of leg mass with respect to the mass of the rest of the body?
How to sum joint powers and leg powers?
The relative contribution of passive structures to mechanical work?
Actual sources of mechanical work?

Strengths and Limitations
CLM is simple but assumes the legs are massless and allows for power transfer between them.
JPM is more anatomically accurate but, it requires measurement of a rather large, and difficult to accurately measure, data set that includes segment kinematics and inertial parameters. Can only assign work to defined DOFs.
For walking, ILM is a good compromise.

Individual Limbs Method

Raw forces
Trimmed Forces

Center of Mass Velocity

\[ \sum \vec{F} = \vec{F}_{\text{trail}} + \vec{F}_{\text{lead}} + m\vec{g} \]

\[ \vec{a}_{\text{com}} = \frac{\vec{F}_{\text{total}}}{m} \]

\[ \vec{v}_{\text{com}} = \int_{t_i}^{t_f} \vec{a}_{\text{com}} \, dt + \vec{c} \]

Individual Limb Power

\[ P_{\text{trail}} = \vec{F}_{\text{trail}} \cdot \vec{v}_{\text{cm}} \]

\[ P_{\text{lead}} = \vec{F}_{\text{lead}} \cdot \vec{v}_{\text{cm}} \]

Forces, velocities and power

(Donelan, Kram and Kuo, 2002)
Mechanical work

\[ W_{\text{trail}} = \int P_{\text{trail}} \, dt \quad W_{\text{load}} = \int P_{\text{load}} \, dt \]

\[ W_{\text{ILM}} = W_{\text{trail}} + W_{\text{load}} \]

Efficiency

\[ \text{Efficiency} = \frac{\Delta \text{mechanical work}}{\Delta \text{metabolic cost}} \]

Efficiency – Slope Walking

Maximum positive efficiency: \( \sim 25\% \)

Maximum negative efficiency: \( \sim -120\% \)

Thus, 1J of positive work will require a minimum of 4J of metabolic energy and -1J of negative muscle work will require a minimum of 0.83J.

The effective efficiency is defined as the ratio of positive work to the total metabolic cost:

\[ \frac{1 \text{J}}{4.83 \text{J}} = 0.21 \text{ (or 21\%)} \]

(Brooks et al., 2005)
Minimizing metabolic cost explains human walking biomechanics

Determinants of Gait?
1. pelvic rotation
2. pelvic tilt
3. knee flexion during stance
4&5. plantarflexion during heel strike and heel off
6. lateral displacement of pelvis
7. ankle inversion-eversion-inversion during stance
8. lateral flexion of trunk
9. anteriorposterior flexion of trunk

What determines metabolic cost?

Isolated muscle
metabolic cost $\propto$ mechanical work

Cycling, rowing, and slope walking
metabolic cost $\propto$ mechanical work

Level walking.
net mechanical work = 0; Metabolic cost $\propto$ ?
Inverted Pendulum Model of Walking

(Cavagna, 1976)

Step-to-step transition

Transitions require negative work

Transitions require negative work

heel strike, $\delta$

$\vec{v}_{cm}^+ < \vec{v}_{cm}^-$
Positive work best performed simultaneously

Individual limbs mechanical work

\[ P_{\text{trail}} = F_{\text{trail}} \cdot \ddot{v}_{\text{cm}} \]
\[ P_{\text{lead}} = F_{\text{lead}} \cdot \ddot{v}_{\text{cm}} \]

\[ W_{\text{trail}} = \int P_{\text{trail}} \, dt \]
\[ W_{\text{lead}} = \int P_{\text{lead}} \, dt \]

Leading leg is a brake and the trailing leg is a motor

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Power (W) vs. Time (s)

Rate of COM Work (W/kg) vs. Gait Cycle (%)

- Collision
- Rebound
- Pre-load
- Push-off
Work increases with step length

Dynamic walking models make testable predictions about human walking mechanics and energetics

Simplest 2-D Walking Model

Anthropomorphic 3-D Walking Model

Length-modulated walking

Transition Work Predictions

Leg Motion Prediction

\[ P_{\text{mech}} = C_{\text{trans}} l^4 + C_{\text{swing}} l^2 + D \]

\[ P_{\text{net}} = C'_{\text{trans}} l^4 + D' \]
Length-modulated walking

Work increases with step length

Work and metabolic cost increase with step length

Efficiency
**Accounting**

Preferred Speed Walking (1.25 m/s):

\[ P_{\text{trans}} = 0.35 \text{ (W/kg)} \]

\[ P_{\text{met}} = 2.51 \text{ (W/kg)} \]

\[ \text{Eff} = \frac{\text{mechanical work}}{\text{metabolic cost}} = 0.21 \]

\[ \% = \frac{P_{\text{trans}}}{P_{\text{met}} \cdot \text{Eff}} \cdot 100 = 66\% \]

**Transition work decreases with step frequency**

**Cost to increasing step frequency?**

![Graph showing step length vs. speed](image)

**Limb Swing Cost**

Isolated leg swinging

Frequency modulated walking

Experiment by Jiro Doke and Art Kuo
Limb Swing Cost

Isolated leg swinging

Frequency modulated walking

Minimizing metabolic cost explains human walking biomechanics

Walking is passively unstable in the lateral direction

External Lateral Stabilization

(Atzler and Herbst, 1927; Eiflman, 1967; Kuo, 2001)
External Lateral Stabilization

- Step width variability decreased by 33%
- Metabolic cost decreased by 9%
- Average step width decreased by 47%

Pentapedal Walking

Hemiparetic Gait
Useful references


