Gaits and Locomotion

• Locomotion
• Metabolic energy
• Gaits
• Partial gravity simulation
Hopping (Airless Flat Planet)

Use $F=ma$ for vertical motion

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

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

Constant velocity in horizontal direction produces

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

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

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

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

$$\gamma_{opt} = \frac{\pi}{2} = 45^\circ$$

$$d_{max} = \frac{V^2}{g}$$

$$V = \sqrt{gd}$$

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

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

$$V_v = \frac{V}{\sqrt{2}}$$

$$h_{max} = \frac{V^2}{4g} = \frac{\sqrt{gd}^2}{4g} = \frac{d}{4}$$
Propulsive Gliding (Airless Flat Planet)

Assume horizontal velocity is \( V \)

\[
\Delta V_h = 2V
\]

(includes acceleration and deceleration)

\[
t_{flt} = \frac{d}{V}
\]

Total \( \Delta V \) 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

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

$$2 - \frac{gd}{V^2} = 0$$

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

$$\Delta V_{total} = 2\sqrt{\frac{gd}{2}} + gd\sqrt{\frac{2}{gd}} = 2\sqrt{2}\sqrt{gd}$$
Delta-V for Hopping and Gliding

![Graph showing Delta-V (m/sec) vs. Distance (m) for Ballistic Hop and Propulsive Glide.](image)

- **Ballistic Hop**
- **Propulsive Glide**

The graph illustrates the relationship between Delta-V and Distance for both hopping and gliding. The curves show the increase in Delta-V with increasing distance, with the propulsive glide having a higher Delta-V at any given distance compared to the ballistic hop.
Nondimensional Forms

Define \( \nu \equiv \frac{V}{\sqrt{d g}} \quad \rho \equiv \frac{d}{r} \quad \eta \equiv \frac{h_{max}}{d} \)

\( \nu_{\text{flat glide}} = 2\sqrt{2} \)

\( \nu_{\text{flat hop}} = 2 \quad \eta = \frac{1}{4} \)

\( \nu_{\text{spherical glide}} = 2\sqrt{2 - \rho} \quad (0 \leq \rho \leq 1) \)
**Multiple Hops**

- Assume \( n \) hops between origin and destination
- At each intermediate “touchdown”, \( v_v \) has to be reversed

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

\[
t_{peak} = \frac{V_v}{g}
\]

\[
t_{total} = 2nt_{peak} = 2n \frac{V_v}{g}
\]

\[
d = V_h t_{total} = \frac{2n}{g} V_h V_v
\]

\[
V_v = \sqrt{2gh_{max}}
\]

\[
\nu_v = \sqrt{\frac{2\eta}{n}}
\]

\[
\nu \equiv \frac{V}{\sqrt{dg}}
\]

\[
\eta \equiv \frac{h_{max}}{d/n}
\]

\[
V_h = \frac{dg}{2nV_v}
\]

\[
\nu_h = \frac{1}{2} \sqrt{\frac{1}{2n\eta}}
\]
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

\[ \eta_{opt} \] vs. Number of Hops (n)

\[ \Delta \nu \] vs. Number of Hops (n)
Walking and Running Gaits

Implications of Pendulum Motion

- Basic period of a pendulum

\[ P \approx 2\pi \sqrt{\frac{L}{g}} \]

- Inertias of point and distributed masses

\[ I = mL^2 \quad \text{and} \quad I = \frac{1}{3}mL^2 \]

- For 0.75 m leg length, \( P_{\text{walking}} \approx 1.0 \text{ sec (on Earth)} \)
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 \( \sim Fr=0.5 \)
Metabolic Costs of Physical Exertion

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

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

from Roth, *Bioenergetics of Space Suits for Lunar Exploration*, NASA SP-84, 1966
O₂ Requirement to Walk and Run

from Roth, *Bioenergetics of Space Suits for Lunar Exploration*, NASA SP-84, 1966
O₂ Requirement to Walk and Run

from Roth, Bioenergetics of Space Suits for Lunar Exploration, NASA SP-84, 1966
Effect of Stride and Cadence

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

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

Gait Footfalls


Gaits and Locomotion
MIT Gravity Offset System

MIT Exoskeletal Suit Joint Simulator

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)

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
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<tbody>
<tr>
<td>6</td>
<td>No exertion at all</td>
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<tr>
<td>7</td>
<td>Extremely light</td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Very light</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Light</td>
</tr>
<tr>
<td>12</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Somewhat hard</td>
</tr>
<tr>
<td>14</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Hard (heavy)</td>
</tr>
<tr>
<td>16</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Very hard</td>
</tr>
<tr>
<td>18</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Extremely hard</td>
</tr>
<tr>
<td>20</td>
<td>Maximal exertion</td>
</tr>
</tbody>
</table>
Corlett & Bishop Discomfort Scale

Discomfort Scale

- 0: Nothing at All
- 0.5: Extremely Low Discomfort
- 1: Very Low Discomfort
- 2: Low Discomfort
- 3: Moderate Discomfort
- 4: High Discomfort
- 5: Very High Discomfort
- 6: Extremely High Discomfort

Front of Participant

Back of Participant
### Speeds Used for Testing

<table>
<thead>
<tr>
<th>Stage</th>
<th>Speed</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X minus 1.1 mph</td>
<td>Subtract 0.3 mph per stage; need smaller increments for walking</td>
</tr>
<tr>
<td>2</td>
<td>X minus 0.8 mph</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>X minus 0.5 mph</td>
<td>Subtract 0.5 mph to assure walking out of transition zone</td>
</tr>
<tr>
<td></td>
<td>PTS = X</td>
<td>No data collected in transition zone</td>
</tr>
<tr>
<td>4</td>
<td>X plus 0.5 mph</td>
<td>Add 0.5 mph to assure running out of transition zone</td>
</tr>
<tr>
<td>5</td>
<td>X plus 1.5 mph</td>
<td>Add 1.0 mph to distinguish metabolic/biomechanical differences at running speeds</td>
</tr>
<tr>
<td>6</td>
<td>X plus 2.5 mph</td>
<td></td>
</tr>
</tbody>
</table>
Shirt-Sleeve Suspension
Suited Partial-Gravity Suspension
Details of Gimbal Mount to Pogo System

Stinger

Spider

Gimbal Support Structure
Test Subject Performing 10 km Traverse
Metabolic Costs of Lunar Locomotion

The graph illustrates the metabolic costs of locomotion in relation to speed on a lunar surface with varying conditions.

- **Uns suited**: Blue diamonds.
- **Uns suited weight-matched**: Red squares.
- **Suited**: Green triangles.
- **1g**: Blue crosses.

The graph shows that metabolic cost increases with speed, and the type of suit (unsuited, suited) affects the metabolic cost, with suited individuals generally having lower metabolic costs at higher speeds compared to unsuited individuals.
O2 Transport Cost of Lunar Locomotion

![Graph showing O2 transport cost vs speed for different conditions: Unsuit, Unsuit w/matched, Suited, and 1g.](image)
Cooling and Energy Use in Lunar Run

![Graph showing the relationship between speed and energy use.](image)

- **CO₂ Transport (ml·kg⁻¹·km⁻¹)**
- **Heat Production (BTU·hr⁻¹·ft⁻²)**

- **15 Minute Cooling Limit** for Shuttle EVA Suits
References for This Lecture

