Feasibility of Suited 10-km Ambulation “Walkback” on the Moon

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Introduction

Are 1 or 2 surface rovers required to enable safe and efficient human exploration of the Moon?

- Increased mass, volume, and cost associated with launch and transport of two rovers
- May not be necessary if crewmembers could walk back to habitat if rover failed
- 10-km “walkback” used as starting point based on:
  - Apollo program
  - Anticipated lunar surface operational concepts
Objectives

• Primary objective: Collect biomedical and human performance data and produce a crew consensus regarding the feasibility of performing a suited 10-km walkback

• Secondary objectives:
  – Understand specific biomedical and human performance limitations of the suit compared to matched shirt-sleeve controls
  – Collect metabolic and ground-reaction force data to develop an EVA simulator for use on future prebreathe protocol verification tests
  – Provide data to estimate consumables usage for input to suit and portable life support system (PLSS) design
  – Assess the cardiovascular and resistance exercise associated with partial-gravity EVA for planning appropriate exploration exercise countermeasures
Subjects

- **NASA crewmembers**
  - \( n = 6 \)
  - Typically members of the EVA Branch
- **Good fit with MKIII EVA Suit**
- **All males**
  - Females were not excluded, but were not included either due to inadequate suit fit or unavailability
- **Current Air Force Class III physical**

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>46.8 ± 4.3</td>
<td>40 - 51</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180.3 ± 5.0</td>
<td>175 - 188</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>81.4 ± 7.8</td>
<td>71.2 - 89.4</td>
</tr>
<tr>
<td>( \text{VO}_2\text{pk} ) (ml(\cdot\text{kg}^{-1}\cdot\text{min}^{-1})</td>
<td>48.7 ± 5.7</td>
<td>40.8 - 55.6</td>
</tr>
</tbody>
</table>
Test Hardware

- **Partial gravity simulator (Pogo)**
  - Overhead suspension
  - Spider/gimbal attachment for suited test
  - Spreader-bar and harness for unsuited tests

- **MKIII EVA Suit**
  - Hybrid of hard (torso/brief) and soft (arms/legs) components
  - Multi-axial mobility for planetary environments
  - 121 kg total suit weight

- **Challenger Treadmill**
  - COTS product
  - 27" x 72" walking surface
  - Mounted forceplates at each corner
Testing Protocols

- **VO$_2$pk Test (Treadmill)**
- **Preferred Transition Speed (PTS) Determination**
  - Walk to run transition determined at 1/6 g and 3/8 g both unsuit and suited
- **Unsuit Energy-Velocity Test**
  - 3 minutes at 6 different speeds (3 below PTS and 3 above PTS), 0% grade
  - 1 g, 1/6 g, 3/8 g, 1/6 g weight-matched, 3/8 g weight-matched
- **Suited Energy-Velocity Test**
  - 3 minutes at 6 different speeds (3 below PTS and 3 above PTS), 0% grade
  - 1/6 g, 3/8 g
- **Suited 10 km Walkback Test**
  - Unlimited time to complete 10 km on level treadmill at 1/6 g
Data Collected

- **Physiological Data**
  - Oxygen consumption, CO$_2$ production, etc.
  - Heart rate
  - Skin and core temperatures (limited)

- **Biomechanical Data**
  - Ground reaction forces (GRF)
  - Gait parameters (stride length, cadence, etc.)
  - Kinematics

- **Subjective Measures**
  - Rating of Perceived Exertion
  - Modified Cooper-Harper Scale (operator compensation, controllability)
  - Discomfort Scale (Corlett and Bishop)

- **Video/Photo**
  - All sessions were videotaped
  - Photos taken of any medical or discomfort issues for later use in suit trauma countermeasures work
### Subjective Measurements

**HANDLING QUALITIES RATING SCALE**

<table>
<thead>
<tr>
<th>ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION*</th>
<th>CONTROL CHARACTERISTICS</th>
<th>DEMANDS ON OPERATOR IN SELECTED TASK OR REQUIRED OPERATION*</th>
<th>Operator RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is it satisfactory without improvement?</td>
<td>Excellent</td>
<td>Operator compensation not a factor for</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Highly desirable</td>
<td>desired performance - easier than 10 activity</td>
<td></td>
</tr>
<tr>
<td>Is it controllable?</td>
<td>Good</td>
<td>Operator compensation not a factor for</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Negligible deficiencies</td>
<td>desired performance - equivalent to 10 activity</td>
<td></td>
</tr>
<tr>
<td>Does it warrant improvement?</td>
<td>Fast - some mildly</td>
<td>Minimal operator compensation required for</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>unpleasant deficiencies</td>
<td>desired performance</td>
<td></td>
</tr>
<tr>
<td>Is it adequate performance attainable with a</td>
<td>Minor but annoying</td>
<td>Desired performance requires moderate operator</td>
<td>4</td>
</tr>
<tr>
<td>tolerable pilot workload?</td>
<td>deficiencies</td>
<td>compensation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moderately objectionable</td>
<td>Adequate performance requires considerate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>deficiencies</td>
<td>operator compensation</td>
<td></td>
</tr>
<tr>
<td>Does it require improvement?</td>
<td>Very objectionable but</td>
<td>Adequate performance requires extensive operator</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>tolerable deficiencies</td>
<td>operator compensation</td>
<td></td>
</tr>
<tr>
<td>Is it controllable?</td>
<td>Major Deficiencies</td>
<td>Adequate performance not attainable with</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>maximum tolerable operator compensation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Controllability not in question.</td>
<td></td>
</tr>
<tr>
<td>Does improvement mandatory?</td>
<td>Major Deficiencies</td>
<td>Considerable operator compensation is required</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>for control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Major Deficiencies</td>
<td>Intense operator compensation is required to</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>retain control - equivalent to 10 activity</td>
<td></td>
</tr>
<tr>
<td>Does improvement mandatory?</td>
<td>Major Deficiencies</td>
<td>Control will be lost during some portion of the</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>required operation - more difficult than 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>activity</td>
<td></td>
</tr>
</tbody>
</table>

* Definition of required operation involves designation of tight praise and/or subspace with accompanying conditions.
Subjective Measurements

**Discomfort Scale**

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Nothing at All</td>
</tr>
<tr>
<td>0.5</td>
<td>Extremely Low Discomfort</td>
</tr>
<tr>
<td>1</td>
<td>Very Low Discomfort</td>
</tr>
<tr>
<td>2</td>
<td>Low Discomfort</td>
</tr>
<tr>
<td>3</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>4</td>
<td>High Discomfort</td>
</tr>
<tr>
<td>5</td>
<td>Very High Discomfort</td>
</tr>
<tr>
<td>6</td>
<td>Extremely High Discomfort</td>
</tr>
<tr>
<td>7</td>
<td>Maximal exertion</td>
</tr>
</tbody>
</table>

**RPE**

- 6: No exertion at all
- 7: Extremely light
- 8: Very light
- 9: Light
- 10: Somewhat hard
- 11: Hard (heavy)
- 12: Very hard
- 13: Extremely hard
- 20: Maximal exertion

“Feasibility of Suited 10 km Walkback on the Moon” - Jason Norcross
Examples of Suited and Unsuited Locomotion

• Differences include:
  – Weight
  – Inertial mass
  – Pressure
  – Kinematic constraints
  – Stability
  – Overhead suspension methods
Energy-Velocity Series Results - Moon

**Metabolic Cost**

- **Moon, suited (●)**
- **Moon, unsuited (△)**
- **Moon, unsuited / weighted (♦)**
- **Earth, unsuited (×)**

**Total Metabolic Cost of Suit**

Inertial Mass
Kinematics
Pressure
Weight Factors

**Transport Cost**

- **Moon, suited**
- **Earth, unsuited**
- **Moon, unsuited**
- **Moon, unsuited weighted**

“Feasibility of Suited 10 km Walkback on the Moon” - Jason Norcross
Energy-Velocity Series Results - Mars

Metabolic Cost

Transport Cost

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**Implications for Walkback**

1. **Faster speeds provide improved efficiency, but require higher per-minute metabolic cost.**

2. **Cooling may be a limiting factor.**

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### 10 km Walkback Summary

#### 10 km Walkback Summary Data

(averaged across entire 10 km unless noted)

<table>
<thead>
<tr>
<th>Measure</th>
<th>MEAN</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg walkback velocity (mph)</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Time to complete 10 km (min)</td>
<td>95.8</td>
<td>13</td>
</tr>
<tr>
<td>Avg %VO₂pk</td>
<td>50.8%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Avg met rate (BTU/hr)</td>
<td>2374</td>
<td>303.9</td>
</tr>
<tr>
<td>Max. 15-min-avg met rate (BTU/hr)</td>
<td>2617</td>
<td>315</td>
</tr>
<tr>
<td>Total energy expenditure (kcal)</td>
<td>944.2</td>
<td>70.5</td>
</tr>
<tr>
<td>RPE</td>
<td>11.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Cooper-Harper</td>
<td>3.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Water used for drinking (oz)</td>
<td>~24-32</td>
<td>N/A</td>
</tr>
</tbody>
</table>

#### Planning / PLSS Sizing Data

<table>
<thead>
<tr>
<th></th>
<th>Walkback</th>
<th>Apollo</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Usage</td>
<td>0.4 lbs/hr</td>
<td>0.15 lbs/hr</td>
</tr>
<tr>
<td>BTU average</td>
<td>2374 BTU/hr</td>
<td>933 BTU/hr</td>
</tr>
<tr>
<td>Cooling water</td>
<td>3.1 lbs/hr</td>
<td>0.98 lbs/hr</td>
</tr>
<tr>
<td>Energy expenditure</td>
<td>599 kcal/hr</td>
<td>233 kcal/hr</td>
</tr>
</tbody>
</table>
Key Findings

• Suited locomotion had higher metabolic rates than unsuited and unsuited weight-matched controls

• Locomotion in Mars gravity required higher metabolic rates than Moon gravity for both suited and unsuited trials
  – MKIII EVA Suit functioned acceptably throughout all speeds on the Moon, but was extremely limited on Mars

• Lunar transport cost decreased as speed increased and leveled off around 4 mph, but these improvements in efficiency may be offset by limited cooling capacity to handle the higher average metabolic rate

• All subjects completed the 10 km walkback and with little difficulty
  – Averages of 51% VO$_2$pk and RPE=12
  – Subjects experimented to find the highest speed they could comfortably tolerate with most stating that cooling was a limiting factor
  – Cooper-Harper of 3.5 ± 1.6 indicates that improvements are warranted
  – Average Discomfort rating of 1.5 ± 1.1 (knees, feet, toes)
Study Limitations

- Smooth, level treadmill
- Subjects free to stop at any time
- No hills
- No stress (life not at stake)
- No navigation or real-time troubleshooting
- Subjects’ balance possibly supported by overhead Pogo/gimbal structure
Forward Work

• Determine which components of the suit have the greatest effect on metabolic rate
  – Weight, inertial mass, pressure, center of gravity, kinematic constraints

• Move beyond level locomotion
  – Evaluate exploration tasks (shoveling, picking up rocks, construction)
  – Inclined / declined locomotion

• Evaluate a different suit design

• Evaluate study limitations
  – Increase the operational aspects: time requirements, navigation, troubleshooting
  – Introduce hill profiles
  – Introduce surface variations