ASSESSMENTS OF PHYSIOLOGY AND COGNITION IN HYBRID-REALITY ENVIRONMENTS (APACHE) – PHYSICAL WORKLOAD APPROXIMATION

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Background: Exploration EVA

Exploration EVA differs from Shuttle & ISS EVA in many ways:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current EVA</th>
<th>Exploration EVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tempo</td>
<td>8hr EVA/ ~ 2 months</td>
<td>8hr EVA every other day (24hr/crew/week)</td>
</tr>
<tr>
<td>Environment</td>
<td>Engineered Completely Characterized Microgravity Uncontaminated</td>
<td>Natural &amp; Engineered Incomplete Characterization Partial Gravity Dust</td>
</tr>
<tr>
<td>Tasks</td>
<td>Construction/Maintenance</td>
<td>Science Construction/Maintenance</td>
</tr>
<tr>
<td>Skills / Training</td>
<td>Specific Skills/task-based NBL practice many hours</td>
<td>Generic Skills Tool-based</td>
</tr>
<tr>
<td>Mission</td>
<td>Specific tasks, practiced and planned</td>
<td>Broadly scoped timelines Real-time adjustments</td>
</tr>
<tr>
<td>Operational Support</td>
<td>MCC-centric Extensive personnel support</td>
<td>Crew-centric Delayed ground support</td>
</tr>
</tbody>
</table>
Physical and Cognitive Workload & Fatigue

- Physical activity can affect cognitive performance both positively and negatively
- Risk estimation, decision making, reaction times, coordination, attention, accuracy, and memory may all be compromised during EVA

Physically and cognitively realistic test environments and methods required to inform and validate exploration systems and operations
Limitations of Existing Environments

• Typically either physically realistic OR cognitively realistic
• Limited availability / test time (hardware, facility, in-field time)
• Heavy reliance on small and subjective data sets
• Learning effects and limited repeatability
• Performance measures generally limited and obtrusive
• Difficult / expensive to integrate physiological sensors

Accessible
Affordable
Repeatable
Quantifiable
**APACHE: Goal & Purpose**

- **Goal**: Create a physically and cognitively realistic planetary EVA simulation environment using a combination of virtual reality (VR), physical reality, and hybrid reality (HR).

- **Planned Uses**:
  - Planetary EVA simulation for CHAPEA (and potentially HERA) missions.
  - EVA Walk-back simulation with embedded performance metrics to aid in identifying contingency CO2 limits.
  - Potential future use as xEVA training environment (secondary objective).
Current Capabilities

Current Project Elements
- Vive Pro Eye VR headset has built-in eye tracking technology
- 20ft x 15ft space with Lunar regolith simulant
- Passive treadmill enables long traverses in VR
- Hybrid reality elements
  - Umbilical Interface Assembly (UIA) panel
  - Display and Control Unit (DCU)

Physiology and Cognition
- Weighted suit and variable treadmill resistance settings used to manipulate physical workload
- Various embedded tasks (consumables monitoring, reaction/PVT, object recall) can be added to increase mental workload
Current Capabilities

Virtual Environments

• 1 or 2-player
• Lunar or Martian VR environments
  • Lunar - ~16 km² of explorable terrain around Shackleton Crater, currently built on UE4
  • Mars - ~400 km² of explorable terrain around Jezero Crater, built on UE5
• Integrated Intravehicular Activities (IVA) into sim
• Current EVA tasks
  • Scouting and Exploration
  • Geology (rock chip sample)
  • Science Package Deployment (ALSEP)
  • Dust Mitigation
  • Crowdsourcing additional VR content to piece together multiple, unique end-to-end planetary EVAs (see “NASA MarsXR Challenge”)

Motivation

APACHE

Physical Workload Approximation

Future Work
Physical Workload Approximation

• Treadmill Comparison and JSC Rock Yard
  – Baseline physical workload characterization + comparison to other planetary analogs (JSC Rock Yard + motorized treadmill)

• Weighted Suit Evals
  – Test various configurations of a weighted suit to match APACHE workloads to workloads observed in suited testing (ARGOS)
**Purpose:** To characterize the *voluntary* metabolic rate during ambulation on a passive treadmill in APACHE, in comparison to other planetary analog environments.

<table>
<thead>
<tr>
<th>Walking Environment</th>
<th>Manipulated Parameter(s)</th>
<th>Test Condition</th>
<th>Test Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Yard</td>
<td>Terrain</td>
<td>Generally flat walking path, no obstacles</td>
<td>R1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mixed terrain walking path</td>
<td>R2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generally flat walking path, with obstacles</td>
<td>R3</td>
</tr>
<tr>
<td>Passive Treadmill</td>
<td>Resistance setting</td>
<td>Resistance setting = 1, No VR</td>
<td>P1</td>
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<tr>
<td></td>
<td></td>
<td>Resistance setting = 3, No VR</td>
<td>P2</td>
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<td></td>
<td></td>
<td>Resistance setting = 6, No VR</td>
<td>P3</td>
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<td></td>
<td></td>
<td>Resistance setting = 9, No VR</td>
<td>P4</td>
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<tr>
<td></td>
<td></td>
<td>Resistance setting = 3, with VR</td>
<td>P5</td>
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<tr>
<td></td>
<td></td>
<td>Resistance setting = 6, with VR</td>
<td>P6</td>
</tr>
<tr>
<td>Motorized Treadmill</td>
<td>Grade curve</td>
<td>Walking speed = 1.5mph, Grade = 0%</td>
<td>M1</td>
</tr>
<tr>
<td></td>
<td>Walking Speed</td>
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<td>Walking speed = 3mph, Grade = 0%</td>
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**Motivation**

**APACHE**

**Physical Workload Approximation**

**Future Work**
Baseline Characterization – Methods

• JSC Rock Yard
  – R1: Generally flat, loose gravel path
  – R2: Mixed terrain path including hills, craters, & small obstacles (< 1 m)
  – R3: Generally flat path, including small obstacles

• APACHE Passive Treadmill
  – Discrete treadmill resistances 0-10
  – Evaluated resistances 1, 3, 6, & 9
  – Also tested resistances 3 & 6 while in VR

• Flat, motorized treadmill
  – Walking speeds: 1.5 & 3mph
  – Slope: 0%, 10%, 20% grade
Baseline Characterization – Methods

- 10 subjects
  - 6 male / 4 female
  - Age: 45 ± 5 years old
  - Weight: 65 ± 5 kg
- Protocol
  - Self-paced ambulation at each condition
  - Continued until steady state heart rate was observed
  - 30-sec timer was started. This defined the data range that reported values were averaged from

- Metrics & Hardware:
  - Metabolic rate – Cosmed K5
  - Heart rate – Polar H10
  - Gait – APDM inertial measurement units (IMU’s)

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</table>
Significant difference found between R1-R2 and R2-R3

\[ p_{R1-R2} < 0.0001 \]

\[ p_{R2-R3} < 0.0001 \]
No differences found between VR and non-VR conditions (p = 0.139)
Baseline Characterization – Results

Motivation

APACHE

Physical Workload Approximation

Future Work

No differences found across treadmill resistances (p = 0.40)
Both factors, speed and slope, were found to have significant effects:

- \( p_{\text{SPEED}} < 0.0001 \)
- \( p_{\text{GRADE}} < 0.0001 \)
Baseline Characterization – Results

R1 was significantly different from R2 ($p_{R1-R2} < 0.001$) and R3 ($p_{R1-R3} = 0.008$)
Significant difference was found between VR and non-VR conditions ($p < 0.001$)
Significant effect and positive correlation was found between treadmill resistance and upper body ML displacement ($p < 0.001$).
Baseline Characterization – Results

Significant effect observed for treadmill grade ($p_{\text{GRADE}} < 0.001$) but not for treadmill speed ($p_{\text{SPEED}} = 0.097$)

**Motivation**

**APACHE Physical Workload Approximation**

**Future Work**

[Image of box plots showing upper body sway across test conditions]
Baseline Characterization – Results

- APACHE passive treadmill workloads most similar to...
  - Mixed terrain (R2) condition at rock yard
  - 1.5mph @ 20% (M3)
  - 3.0mph @ 10% (M5)
- Difficulty obtaining lower steady-state workloads (< 20 mL/kg·min) on APACHE passive treadmill
- Condition R3 – effects of avoiding small objects on gait vs metabolic rate
- Upper body ML displacement showed a positive trend with treadmill resistance, unlike with metabolic rate
Baseline Characterization – Discussion

APACHE relevance

• Steady-state metabolic rates ranged from 18.34 to 41.69 mL/kg·min
• However, workload remained relatively consistent across the various treadmill resistances (26.9±4.9 mL/kg·min)
• Difficult to prescribe exact walking speeds in APACHE
  – Can pace subjects through mission timelines and traverse time requirements
• Significant speed decrease observed around treadmill resistance ~6
  – Some treadmill resistance + speed combinations are not practical for APACHE operations

Remaining question: Through mission pacing, what workloads can we achieve on the passive treadmill and still maintain realistic ops?
Baseline Characterization – Discussion

Additional Workload Comparisons

• Apollo EVA metabolic rates
  – Mostly saw metabolic rates in the range of 500-1500 BTU/hr, or 5-16 mL/kg-min
  – Metabolic peaks of 2000 BTU/hr, or 21 mL/kg-min

• Suited ambulation in a Martian gravity simulator
  – Mark III spacesuit used within the Active Response Gravity Offload Simulator (ARGOS) at Johnson Space Center, configured to a Martian gravity offload
  – N = 1
  – Subject ambulated over a powered treadmill at 1.5 mph and varying grade slopes (-10% to 30%)
  – Metabolic rates up to 45 mL/kg-min

• Field testing
  – Shadowed crew traverse routes on recent field test analogs in Flagstaff, AZ
  – N = 3, i.e. 3x different routes, roughly 2-3 hours in duration, wearing ~60 lbs of gear and mostly ambulating with some stationary periods of “simulated geology”
  – Metabolic rates up to 32 mL/kg-min
Future Work

• Similar characterization effort for omnidirectional VR treadmill
• Weighted suit evals
  – Hybrid Spacesuit Simulator (HS3)
  – Test various configurations of a weighted suit to match APACHE workloads to workloads observed in suited testing (ARGOS)
• Characterize both physical and cognitive workloads of a complete end-to-end simulated planetary EVA
Planned Research

• Translation Study (2020)
• Cognitive Workload Measures Development
  – Subject testing to begin Summer 2022
• Physical workload testing & validations
  – Treadmill Comparison & JSC Rock Yard Study (2021)
  – Weighted suit config + evals (2022)
• PersEIDS HITL Proof-of-Concept (2022 Q4)
• CO₂ Walk-back Study (2022-23)
• CHAPEA EVA development & support (2022+)

Motivation  APACHE  Physical Workload Approximation  Future Work
Thank you!

Questions?
Backup Slides
## Baseline Characterization – Results

<table>
<thead>
<tr>
<th>Test code</th>
<th>Metabolic Rate (mL/kg·min)</th>
<th>Heart Rate (bpm)</th>
<th>Upper Body ML Displacement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>16.6 (±3.4)</td>
<td>110 (±11)</td>
<td>15.39 (±3.58)</td>
</tr>
<tr>
<td>R2</td>
<td>25.0 (±5.0)</td>
<td>134 (±17)</td>
<td>26.18 (±7.68)</td>
</tr>
<tr>
<td>R3</td>
<td>16.1 (±3.6)</td>
<td>109 (±11)</td>
<td>24.28 (±5.53)</td>
</tr>
<tr>
<td>P1</td>
<td>26.2 (±4.5)</td>
<td>129 (±15)</td>
<td>12.09 (±2.62)</td>
</tr>
<tr>
<td>P2</td>
<td>25.5 (±4.7)</td>
<td>131 (±17)</td>
<td>14.38 (±4.00)</td>
</tr>
<tr>
<td>P3</td>
<td>29.7 (±5.7)</td>
<td>141 (±14)</td>
<td>18.41 (±4.46)</td>
</tr>
<tr>
<td>P4</td>
<td>26.1 (±4.1)</td>
<td>137 (±13)</td>
<td>25.58 (±9.03)</td>
</tr>
<tr>
<td>P5</td>
<td>26.1 (±4.4)</td>
<td>133 (±15)</td>
<td>11.38 (±2.11)</td>
</tr>
<tr>
<td>P6</td>
<td>28.8 (±4.0)</td>
<td>141 (±12)</td>
<td>14.62 (±2.27)</td>
</tr>
<tr>
<td>M1</td>
<td>12.2 (±2.1)</td>
<td>100 (±9)</td>
<td>14.85 (±4.58)</td>
</tr>
<tr>
<td>M2</td>
<td>17.5 (±2.4)</td>
<td>114 (±13)</td>
<td>18.16 (±5.76)</td>
</tr>
<tr>
<td>M3</td>
<td>24.1 (±2.8)</td>
<td>130 (±14)</td>
<td>22.28 (±7.86)</td>
</tr>
<tr>
<td>M4</td>
<td>15.4 (±1.3)</td>
<td>105 (±7)</td>
<td>12.45 (±3.03)</td>
</tr>
<tr>
<td>M5</td>
<td>27.7 (±1.7)</td>
<td>140 (±12)</td>
<td>17.21 (±4.93)</td>
</tr>
<tr>
<td>M6</td>
<td>40.2 (±3.5)</td>
<td>164 (±10)</td>
<td>18.17 (±3.16)</td>
</tr>
</tbody>
</table>
Translation Study

APACHE Translation Study
3/5/2020

Cognitive Workload Measures Development

Cognitive Workload Study

In partnership with the Fatigue Countermeasures Laboratory at NASA Ames

• **Purpose:**
  - Assess validity of using embedded cognitive performance metrics in comparison to traditional subjective assessments

• **Study Design:**
  - **Condition 1:** Baseline EVA procedure w/ periodic subjective assessments
  - **Condition 2:** EVA procedure + secondary task performance
  - Physiological data in both conditions to support ML & model development

• **Subject testing to begin Summer 2022**
CO₂ Contingency Walk-back

NASA Human Research Program (HRP) funded

**Purpose:**
- Assess physical and cognitive performance impacts of completing a simulated 1-hour contingency walk-back under various CO₂ exposures

**Study Design:**
- 15 subjects
- 1-hour simulated Lunar walk-back
  - Simulated mission timeline + spacesuit constraints
- Modify CO₂ levels via mask (0-30 mmHg equivalent pCO₂ at 4.3psia)

**Measure:**
- Heart rate, metabolic rate, SpO₂, tcpCO₂
- APACHE embedded cognitive performance metrics
- Track symptoms/self-assessment of performance via surveys

Subject testing to begin Fall 2022
CHAPA EVA Development

• CHAPA = Crew Health And Performance Exploration Analog
  – https://www.nasa.gov/chapea
  – 4 crew, 1-year long mission in a Martian habitat analog (located at JSC)
• Goal:
  – To provide multiple unique VR EVAs for the crew to perform + characterize crew performance throughout the analog mission
APACHE: Future Work

- Research! FY22 spent a lot on development, looking forward to lots of research and testing in FY23
- Biosensor feedback -> closed loop simulation
- PersEIDS + Stennis’ NPAS tool for crew state risk model and mission/traverse planning
- Infinadeck integration + testing + overhead safety support
- HS3 integration + testing
- Migrating/upgrading assets to UE5
Hybrid Space Suit Simulator (HS3)

- **Goal:**
  - Low-cost, research-focused physical and cognitive workload simulator
    - Crew loading
    - Biometrics integration
  - Developed in Q1-Q2 FY22
  - Future efforts to compare HS3 against actual suited data
APACHE Crowdsourcing Challenge

• Public crowdsourcing challenge through NASA Tournament Lab
• Goal:
  – To generate additional VR content for APACHE
  – To foster a specialized community, potentially for future VR/content development w/ NTL
• 20 individual prizes
• 5 Challenge Categories:
  1. Set Up Camp
  2. Scientific Research
  3. Maintenance
  4. Exploration
  5. Blow Our Minds
PersEIDS
Personal EVA Informatics & Decision Support

• Collaboration with NASA Stennis’ NPAS tool (NASA Platform for Autonomous Systems)

• Integrates a Crew State Risk Model (CSRM) with step-execution procedures and decision support platforms (NPAS) to predict crew state + make operational recommendations based off crew state
  – Example:
    • Crew is working too hard and burning consumables faster than expected/planned
    • PersEIDS will notify MCC or crew to slow down and/or replan upcoming EVA tasks to keep crew within their “safety envelope”
  – FY22 focused on simple proof-of-concept implementation.