Musculoskeletal Physiology

• Skeletal structures
• Bone chemistry
• Muscle physiology
• Muscle chemistry
• Exercise countermeasures
• Artificial gravity
Skeletal Structure

from Lujan and White, Human Physiology in Space NASA/NIH/USRA/UTSW
Categories of Articulated Joints

from Lujan and White, Human Physiology in Space NASA/NIH/USRA/UTSW
Major Parts of a Long Bone

from Lujan and White, Human Physiology in Space NASA/NIH/USRA/UTSW
Bone Construction and Maintenance

- All bones start out cartilagenous
- Ossification - conversion of cartilage to bone
- Osteoblasts - deposit minerals and salts
- Osteoclasts - break down unused/damaged areas
- Rates of bone growth and harvesting driven by stress on bone
Basic Multicellular Unit in Bone Growth

Calcium Regulation System

from Lujan and White, Human Physiology in Space NASA/NIH/USRA/UTSW
Skylab Early Urinary Calcium Output

Skylab Long-Duration Urine and Fecal Ca
Bone Density - 5-6 Months on Mir

from Nicogossian et. al., Space Biology and Medicine - AIAA, 1996
Efficacy of Countermeasures on Ca Loss

from Nicogossian et. al., Space Biology and Medicine - AIAA, 1996
Functioning of Muscle Fiber

from Lujan and White, Human Physiology in Space NASA/NIH/USRA/UTSW
Muscle Metabolism

- Anaerobic
  \[ ATP \leftrightarrow ADP + P + \text{free energy} \]
  \[ \text{creatine phosphate} + ADP \leftrightarrow \text{creatine} + ATP \]
  \[ \text{glycogen or glucose} + P + ADP \rightarrow \text{lactate} + ATP \]
- Aerobic
  \[ \text{glycogen or fatty acids} + P + ADP + O_2 \rightarrow CO_2 + H_2O + ATP \]
- All conditions
  \[ 2ADP \leftrightarrow ATP + AMP \]
Energy Transfer Kinetics

from Johnson, Biomechanics and Exercise Physiology - John Wiley and Sons, 1991
Changes in Muscle Fibers to Bed Rest

from Nicogossian et. al., Space Biology and Medicine - AIAA, 1996
Long-Term Adaptation to Microgravity

from Nicogossian, Huntoon, and Pool, Space Physiology and Medicine - Lea and Fabiger, 1994
Overall Body Response to Space Flight

from Lujan and White, Human Physiology in Space NASA/NIH/USRA/UTSW
Current ISS Exercise Protocols

- 2.5 hrs/day, 6 days/wk
- Resistance exercise
  - iRED
  - Predominantly high reps low loads
- Aerobic exercise
  - TVIS & CEVIS
  - 30 min continuous at ~70% HRmax
  - Some interval work – “Greenleaf protocol”
Resistive Exercise Equipment on ISS

- Advanced Resistance Exercise Exercise Device (ARED)
ARED Specs (vs. IRED)

- Greater loads – 600 lbs
  - Pneumatic cylinders
    - Constant load
    - Ecc-Con ratio ~90%
  - Flywheels
    - Simulated inertia
- 29 different exercises
- Instrumented
ISS Exercise Equipment

- TEVIS
- CEVIS
- T2 soon
Nominal ARED Maintenance

- ARED Evacuate Cylinder Flywheel – once per week (15 minutes)
- ARED Exercise Rope Replacement – every 31,500 cycles (~2.5 months for 6 CM) (75 minutes x 2 Crewmembers)
- ARED Cable Arm Rope Replacement – every 69,306 cycles (~5.5 months for 6 CM) (60 minutes x 1 Crewmember)
- ARED VIS Rail Inspection – every 2 weeks (10 minutes)
- ARED VIS Rail Greasing - every 2 months (60 minutes)
- ARED Sensor Calibration - once per year (60 minutes x 2 Crewmembers)
New harnesses will arrive on HTV/20S/ULf3/ULF4 as part of an SDTO.
Current harness design will be used along with the new design in a comparison study (on-orbit).
Data will be collected from exercise sessions using both harnesses and a follow-up questionnaire will be completed by participating Crewmembers.
Data will only be collected every 4 exercise sessions.
The instrumentation will also fit on the Current Treadmill Harness.
Current Exercise Not Totally Effective

- ISS crewmembers
  (experiments 1-15, n=18)
  - Isokinetic knee extensor and flexor strength decrease 11% and 17%, respectively.
  - Isokinetic knee extensor and flexor endurance decrease 10% and 9%.
  - Maximal aerobic capacity (estimated from submaximal test) 10% reduction
  - Bone mineral density (BMD) 2-7% decrease depending on site.
New Treadmill - C.O.L.B.E.R.T.

- Better harness & subject loading system
- Instrumented to allow ground reaction force data
- Improved speed
HRP Risks and Gaps

- Risk of impaired performance due to reduced muscle mass, strength and endurance.
  - Gap M7: Can the current in-flight performance be maintained with reduced exercise volume?
  - Gap M8: What is the minimum exercise regimens needed to maintain fitness levels for tasks?
  - Gap M9: What is the minimum set of exercise hardware needed to maintain those (M8) levels?

- Risk of reduced physical performance capabilities due to reduced aerobic capacity.
  - Gaps M7-9: (above)
  - Gap M2: What is the current status of in-flight and post-flight performance capability?
  - Gap CV2: What is VO_{2max} in-flight and immediately post-flight?
Strategy for New Exercise Protocols

• Identify exercise training programs that have been shown to maximize adaptive benefits of people exercising in both 0 and 1 g environments.

• Priority order of evidence
  – ISS or spaceflight information
  – Human flight analog studies (bedrest, unilateral lower limb suspension (ULLS)).
  – Human 1-g exercise training studies
  – Animal flight analogs or 1 g studies only in the rare cases where no human data exist.
## Resistance Exercises - Weekly Schedule

<table>
<thead>
<tr>
<th>Week</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Squat, Bench Press, Romanian Dead Lift,</td>
<td>Dead Lift, Shoulder Press, Single Leg Squat,</td>
<td>Front Squat, Bent-over Row, Single Leg Knee</td>
</tr>
<tr>
<td></td>
<td>Upright Row, Heel Raise</td>
<td>Bent-over Row, Single Leg Heel Raise</td>
<td>Extension, Bench Press, Heel Raise</td>
</tr>
<tr>
<td>1</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
</tr>
<tr>
<td>2</td>
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<td>Light</td>
<td>Light</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Light</td>
<td>Heavy</td>
</tr>
<tr>
<td>4</td>
<td>Heavy</td>
<td>Moderate</td>
<td>Light</td>
</tr>
<tr>
<td>5</td>
<td>Light</td>
<td>Heavy</td>
<td>Moderate</td>
</tr>
<tr>
<td>6</td>
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<td>7</td>
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<tr>
<td>8</td>
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<td>Heavy</td>
<td>Moderate</td>
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<tr>
<td>9</td>
<td>Moderate</td>
<td>Light</td>
<td>Heavy</td>
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<tr>
<td>10</td>
<td>Heavy</td>
<td>Light</td>
<td>Light</td>
</tr>
<tr>
<td>11</td>
<td>Light</td>
<td>Heavy</td>
<td>Moderate</td>
</tr>
<tr>
<td>12</td>
<td>Moderate</td>
<td>Light</td>
<td>Heavy</td>
</tr>
</tbody>
</table>
Aerobic Interval Schedule

- **Short Sprint** - 10 minute warm up at 50% of HRmax, followed by 7-8 sets of maximal exercise for 30 seconds, followed by 15 seconds rest. Increase load after 9 sets.

- **2 minute** - 5 minute warm up at 50% VO₂max, followed by 6x2 minute stages at 70, 80, 90, 100, 90%, 80% VO₂max. The first 5 stages are separated by 2 minute active rest stages at 50% VO₂max. The final stage is a 5 min active rest at 40% VO₂max.

- **4 minute** - 5 minute warm up at ~50% HRmax, followed by intervals of exercise at 90% HRmax. The exercise intervals will be 4x4 min bouts, with 3 min active rest periods.
## Composite Weekly Schedule

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
<th>Day 5</th>
<th>Day 6</th>
<th>Day 7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resistance</strong></td>
<td>35-60 min</td>
<td>35-60 min</td>
<td>35-60 min</td>
<td>35-60 min</td>
<td>35-60 min</td>
<td>35-60 min</td>
<td>35-60 min</td>
</tr>
<tr>
<td><strong>Aerobic Interval</strong></td>
<td>32 min</td>
<td>15 min</td>
<td>35 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Aerobic Continuous</strong></td>
<td>30 min</td>
<td>30 min</td>
<td>30 min</td>
<td>30 min</td>
<td>30 min</td>
<td>30 min</td>
<td>30 min</td>
</tr>
</tbody>
</table>
Human Experience at Partial Gravity

• Time on the Moon
  – Total time: 300 hours
  – Longest single duration: 75 hours
  – Microgravity time prior to landing: 3 days

• Time on Mars
  – Total time: 0
  – Longest single duration: 0
  – Microgravity time prior to landing: 180-260 days
Artificial Gravity

\[ g_{\text{rotation}} = \omega^2 r \]

- **Lunar gravity**
- **Mars gravity**
- **0.5*Earth gravity**
- **0.75*Earth gravity**
- **Earth gravity**
Allowable Rotation Rates

- Select groups (highly trained, physically fit) can become acclimated to 7 rpm
- 95% of population can tolerate 3 rpm
- Sensitive groups (elderly, young, pregnant women) may have tolerance levels as low as 1 rpm
Critical Questions to be Answered

• How does human physiological adaptation vary with gravity level?
• Is there a minimum gravity level that results in acceptable indefinite duration?
• What rotation rates are acceptable, and to which population?
• How does routine variation of gravity level affect human response?
• Do we need artificial gravity for transits to Mars?
Issues with Prior Ground-Based Sims

- Focus is on vestibular adaptation, rather than gravitation-related physiology
- “Long-arm” centrifuges aren’t: most data was collected with rotation radii $\leq 10$ m
- “Long duration” typically hours, up to several days
- Some seminal research performed in non-articulated habitats (faster rotation rates produce larger angles between gravity vector and perpendicular to floor)
- All tests were at resultant gravity levels greater than 1g
Rotating Station from 2001 (1968)
Internal Centrifuge from 2001
Categories of Rotating Stations

- **Monolithic rotation**
  - Entire habitat rotates
  - Issues with docking, external systems
- **Partial system rotation**
  - Habitat portion of station/vehicle rotates
  - Issues with integration, pass-throughs
- **Small arm rotation**
  - Rotation radius comparable to human height
  - High gravitational gradient across body
  - Proposed for beds, exercise equipment, etc.
  - Not further considered here ("equipment", not "habitat")
Three Case Studies

- Taken from output of University of Maryland senior capstone classes in Spacecraft Design
  - Clarke Station (2001)
  - Space Station *Phoenix* (2006)
  - Polus Station (2014)

- Highly detailed publications available (http://spacecraft.ssl.umd.edu/academics/484.archives/484.archive_index.html)

- All three systems intended to provide basic science data on human performance and adaptation to partial gravity levels
Clarke Station (2001)

- Inspired by NASA Gateway studies and arrival of eponymous year of 2001: A Space Odyssey
- Located at Earth-Moon L1
- Capable of operating at all gravity levels between 0 and 1g
- Basic concept of operations:
  - Multiple 6-month missions at constant gravity levels
  - Full-duration simulated opposition-class Mars mission
  - (Same CONOPS will be adopted for all three case studies)
Space Station *Phoenix* (2006)

- Concept was to reutilized International Space Station components to perform artificial gravity studies rather than deorbit at end-of-life
- Located in low Earth orbit
- ISS truss formed main structural element
- Additional structure designed to take rotating gravity loads
- Inflated tunnels allow crew movement between habitats
- Minimized new development and launch costs
Phoenix Reuse of ISS Components
Polus Station

- Modular evolutionary low-cost approach
  - Habitat in microgravity used to support extended exploration during Asteroid Redirect Mission (lunar distant retrograde orbit)
  - Add elements for rotation and perform six-month science studies at various gravity levels
  - Add elements for simulation and perform full-duration Mars simulated mission without resupply

- Hard budget cap of $3B/year
- Limited to only one SLS-1b cargo launch per phase
Polus Configuration (Phase 2)
## Basic Spin Parameters of Stations

<table>
<thead>
<tr>
<th></th>
<th>Clarke</th>
<th>Phoenix</th>
<th>Polus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spin Radius (m)</strong></td>
<td>68</td>
<td>44</td>
<td>56</td>
</tr>
<tr>
<td><strong>Earth spin rate (rpm)</strong></td>
<td>3.62</td>
<td>4.5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Mars spin rate (rpm)</strong></td>
<td>2.22</td>
<td>2.77</td>
<td>2.47</td>
</tr>
<tr>
<td><strong>Moon spin rate (rpm)</strong></td>
<td>1.45</td>
<td>1.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>
# Program Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Clarke</th>
<th>Phoenix</th>
<th>Polus</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Mass</td>
<td>315 MT</td>
<td>254 MT*</td>
<td>126 MT</td>
</tr>
<tr>
<td>Launches</td>
<td>49 Delta IV H, 6 Shuttle</td>
<td>16 Delta IV H</td>
<td>3 SLS, 5 Falcon Heavy</td>
</tr>
<tr>
<td>Cost ($FY14)</td>
<td>$66.1B</td>
<td>$17.4B</td>
<td>$20.7B</td>
</tr>
</tbody>
</table>

* Does not include 300 MT mass of ISS reuse components
Discussion of Design Issues

- Spin rate
- Coriolis acceleration
- Dynamic stability
- Mass and stiffness
- Spin up/spin down
- Crew habitat configurations
- Crew access
- Extravehicular activities
- Crew escape
Spin Rate

- Ground-based testing indicates that tolerance of rotation rate varies from 1-10 rpm
  - 1 rpm for sensitive groups (e.g., pregnant women)
  - 10 rpm for limited group with stepwise acclimatization
- Tolerance limit for 90% of the population probably 3-4 rpm
Coriolis Acceleration

- Motion in spin direction causes change in apparent vertical acceleration
- Motion in radial direction causes tangential acceleration
Crew Habitat Configurations

- Toroidal
  - Provides very large volume and floor area
  - Massive (or very small toroid minor diameter)
- Single floor
  - Closer to consistent gravity conditions
  - e.g., 8 m habitat on 50 m spin - max gravity error 0.3% magnitude, 4.6° from vertical
- Multiple floors
  - Different gravity levels on each floor
  - e.g., 50 m spin - 4% change in gravity per 2 m floor
Intermodule Access

• Habitats on different arms may require crew transfer under spin
  – Interpersonal dynamics for isolated teams
  – Limited skill sets (e.g., doctors)
  – Unique equipment and facilities

• Pressurized tubes to spin axis
  – Length=2r
  – Work to climb to spin axis = \( \frac{mg_{nom}r}{2} \)

• Pressurized circumferential transit tunnel
  – Length=\( \theta r \) - exceeds radial tunnels if angle>115°
  – Requires cable bracing - radial and transverse
Extravehicular Activity

- Required on regular intervals for all habitats to date
- ISS demonstrates need for near-term contingency EVA capability
- EVA under spin is mountain climbing in a spacesuit
- Potential mitigation strategies:
  - Maximize systems inside pressure hull
  - Design gravity accommodations at all EVA sites (e.g., hoists, scaffolds, restraint systems)
  - Budget propellant for regular and contingency spin down/up cycles for maintenance
Crew Rotation and Escape

• Docking under spin only feasible along spin axis
  – May require despun docking adapter
  – Problem with more than 1-2 spacecraft
  – Spin axis is valuable territory (e.g., antennas, arrays)

• Current policy is to always have means of safe escape/EDL for every crew
  – Spacecraft docking adapters not designed for stress of holding spacecraft under gravity loads
  – Dramatic impact on both spacecraft and station due to departure under spin
  – Alternative is reliable access to axis under spin
Human Factors of Life Under Spin

• Acclimatization to variations in gravity level
  – Multiple floor habitats
  – Routine access to/through hub
  – Effect of short-period microgravity on physiology studies of fractional gravity levels

• Interacting with outside world
  – Windows show rotating environment (sensory conflict)
  – Effect of external illumination (sunlight through windows sweeping through station every 15 seconds or so)
Conclusions

• Designing and operating a variable gravity habitat is crucial for human risk mitigation prior to Mars mission
• Stations can be created at reasonable cost and launch mass by adopting new technologies (e.g., active cable control)
• While a rotating habitat will teach us critical issues about survival on Mars, we still don’t know everything we need to know about designing and operating rotating habitats
References