Musculoskeletal Physiology

- Artificial gravity
- Skeletal structures
- Bone chemistry
- Muscle physiology
- Muscle chemistry
- Exercise countermeasures
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
References


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

Low Blood Calcium
- Parathyroid glands sense low blood Ca
- Secretion of parathyroid hormone (PTH)
- Hormone stimulates osteoclast activity
- Reabsorption of bone releases Ca into blood

Normal Range
- Blood Ca rises toward normal

High Blood Calcium
- Thyroid gland senses high blood Ca
- Secretion of calcitonin
- Hormone stimulates osteoblast activity
- Formation of bone removes Ca from blood

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

\[
ATP \Leftrightarrow ADP + P + \text{free energy}
\]

\[
\text{creatinine phosphate} + ADP \Leftrightarrow \text{creatinine} + ATP
\]

\[
\text{glycogen or glucose} + P + ADP \Rightarrow \text{lactate} + ATP
\]

- 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 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)
Experimental Download Harness

Harness SDTO

- 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 (expeditions 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

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<th>Week</th>
<th>Day 1</th>
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<th>Day 3</th>
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<tbody>
<tr>
<td></td>
<td>Squat, Bench Press, Romanian Dead Lift,</td>
<td>Dead Lift, Shoulder Press, Single Leg</td>
<td>Front Squat, Bent-over Row, Single Leg</td>
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<tr>
<td></td>
<td>Upright Row, Heel Raise</td>
<td>Squat, Single Leg Heel Raise</td>
<td>Knee Extension, Bench Press, Heel Raise</td>
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<td>1</td>
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<td>12</td>
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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% VO2 max. 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>
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<tr>
<th></th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
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<td><strong>Resistance</strong></td>
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<td><strong>Aerobic Continuous</strong></td>
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References