

## Exercise Overview

OCHMO-TB-031



## Executive Summary

The human cardiovascular and skeletal muscle systems have evolved to meet the challenges of upright posture in the Earth's gravitational environment. During spaceflight, astronauts experience altered gravity environments that lead to physiological decrements in aerobic capacity, muscle strength, bone strength, vision changes, and altered vascular motility, which can lead to a decrease in crew performance. Exercise is prescribed to astronauts as a countermeasure to altered gravity and is vital to maintaining optimal crew health and performance. It addresses these decrements and is also used as a countermeasure for orthostatic intolerance and immune and sensorimotor functioning.

The extent of physiological deconditioning varies per individual and is dependent on a multitude of factors such as starting fitness level, age, mission duration, and gravity level. Without intervention, acute deconditioning begins immediately upon exposure to an altered gravity environment and is measurable within a few days. As mission duration increases, the decrements will continue to increase without intervention. NASA has generated standards/thresholds to protect health outcomes and enable performance for mission tasks.



## Relevant Technical Requirements

### NASA-STD-3001 Volume 1, Rev C

[V1 3017] Post-Mission Reconditioning

[V1 4001] Microgravity EVA Aerobic Capacity

[V1 4002] Extraterrestrial Surface EVA Aerobic Capacity

[V1 4003] In-Mission Aerobic Capacity

[V1 4004] Post-Mission Aerobic Capacity

[V1 4023] Pre-Mission Muscle Strength and Function

[V1 4024] In-Mission Skeletal Muscle Strength

### NASA-STD-3001 Volume 2, Rev D

[V2 7038] Physiological Countermeasures Capability

[V2 7040] Physiological Countermeasure Operations

[V2 7043] Medical Capability

[V2 8001] Volume Allocation

### Houston We Have a Podcast:

The Body in Space with Gary Jordan Victor Glover and Tom Cruise





## Background

### Health Technical Requirements

These health technical requirements from the NASA Space Flight Human-Systems Standards were chosen based on the ability to mitigate short and long-term health and performance effects, and the ability for crewmembers to return to preflight values for aerobic capacity and muscle strength during the rehabilitation period within 45 days postflight. For bone mineral density (BMD), NASA crewmembers are initially selected with normal bone mineral density and for many crewmembers, it requires a year to recover back to preflight values. If crew are selected with lower BMD, long term consequences need to be considered.

#### *From NASA-STD-3001 Volume 1, Rev C*

##### 4.1.3 In-Mission **Aerobic Capacity**

[V1 4003] The in-mission aerobic capacity **shall** be maintained, either through countermeasures or work performance, at or above 80% of the pre-mission capacity determined by either direct or indirect measures

##### 4.6.2 In-Mission **Skeletal Muscle Strength**

[V1 4024] Countermeasures **shall** maintain in-mission skeletal muscle strength at or above 80% of baseline values.

##### 4.7.2 In-Mission **Bone** Countermeasures

[V1 4027] Countermeasures **shall** maintain bone mineral density (BMD) of the hip and spine at or above 95% of pre-mission values and at or above 90% for the femoral neck.

##### 3.1.16 **Post-Mission Reconditioning**

[V1 3017] All programs **shall** provide the planning, coordination, and resources for an individualized post-mission reconditioning program, specific to each crewmember, mission type, and mission duration. The post-mission reconditioning starts with crew egress at landing and includes a guided, phased reconditioning protocol. The goals of the reconditioning program include the following:

- a. To ensure the health and safety of returning crew.
- b. To actively assist the crew's return to full functional abilities and return-to-flight status.
- c. To actively assist in the crew's return to pre-mission fitness



## Background

### Fitness for Duty/Performance Requirements

The following health technical requirements from the NASA Space Flight Human-Systems Standards were generated based on past EVA experience for NASA astronauts and research data for muscle strength. These requirements are not absolute thresholds, crewmembers may fall below these levels and potentially require more time and resources to accomplish mission tasks. Each operational activity should factor in crewmember fitness and be planned accordingly.

*From NASA-STD-3001 Volume 1, Rev C*

#### 4.1.1 Microgravity EVA Aerobic Capacity

[V1 4001] Crewmembers **shall** maintain an in-mission  $VO_{2max}$  at or above 32.9 ml/(min/kg) for missions with microgravity EVAs as determined by either direct or indirect measures.

#### 4.1.2 Extraterrestrial Surface EVA Aerobic Capacity

[V1 4002] Crewmembers **shall** maintain an in-mission  $VO_{2max}$  at or above 36.5 ml/(min/kg) for missions with extraterrestrial surface EVAs as determined by either direct or indirect measures.

#### 4.6.1 Pre-Mission Muscle Strength and Function

[V1 4023] Pre-mission muscle strength and function **shall** be per the values in Table 4.6-1—Pre-Mission Muscle Strength Technical Requirements.

**Table 2—Pre-Mission Muscle Strength Requirements**

	Minimum	Microgravity EVAs	Celestial Surface EVAs	Unaided Egress
Deadlift	1.0 × Body Weight	1.3 × Body Weight	1.6 × Body Weight	1.3 × Body Weight
Bench Press	0.7 × Body Weight	0.8 × Body Weight	1.0 × Body Weight	0.7 × Body Weight



## Reference Data

### Aerobic Capacity – $\dot{V}O_{2\max}$

$\dot{V}O_{2\max}$  measures the maximum rate a body can absorb and use oxygen. During exercise, cells take oxygen ( $O_2$ ) and create energy which fuels exercise and allows performance of activities. The higher the  $\dot{V}O_{2\max}$ , the greater the ability to complete activities.  $\dot{V}O_{2\max}$  is most accurately tested using a gas analyzer (see right) that measures the volume of  $O_2$  inhaled and exhaled, as the intensity of the exercise increases until the  $O_2$  consumption levels off indicating a max capacity for using  $O_2$  to fuel the work being performed, beyond which the body will have to rely on anaerobic metabolism. Aerobic exercise helps to maintain  $\dot{V}O_{2\max}$  levels.

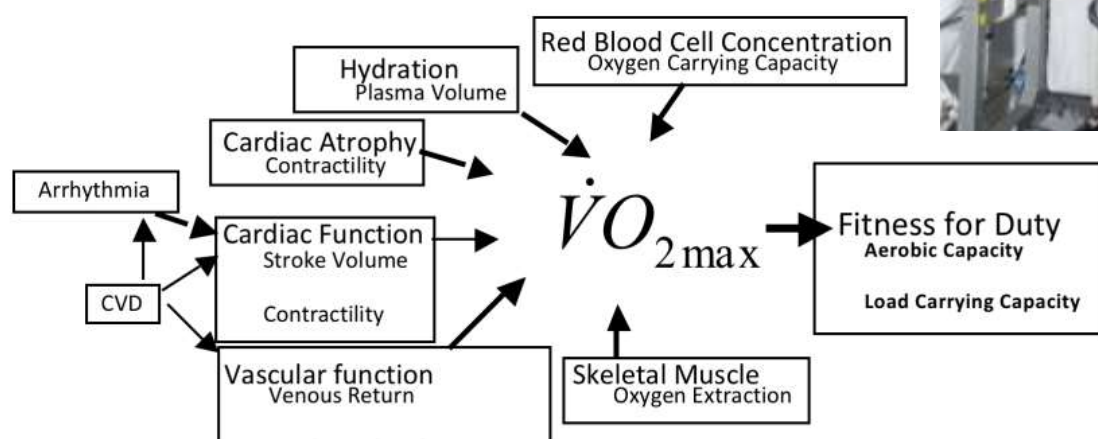


Figure above: *Cardiovascular Effects on performance and Operational Limitations.*

$\dot{V}O_{2\max}$  aerobic capacity = Heart Rate + Stroke Volume + arteriovenous oxygen difference [a- $\dot{V}O_2$ ]  
Encompasses the transport and utilization of oxygen

Factors that affect delivery of  $O_2$  to the active muscles include heart rate (HR), stroke volume (SV, the volume of blood expelled from the heart with each beat), cardiac output (Qc, product of HR and SV), and extraction of  $O_2$  from the arterial blood vessels by the muscles (measured as arteriovenous  $O_2$ , A-V  $O_2$ , difference). The relationship between  $\dot{V}O_2$ , Qc, and A-V  $O_2$  difference is quantified by the Fick equation (Rowell 1986).

$$\dot{V}O_2 = Qc \times A-V O_2 \text{ difference}$$

Note: To Convert l/min to ml/(min/kg):

(l/min x 1000 ml/min)/body weight in kg Example:  $1.17 \times 1000\text{ml/min}/80 \text{ kg} = 14.63$



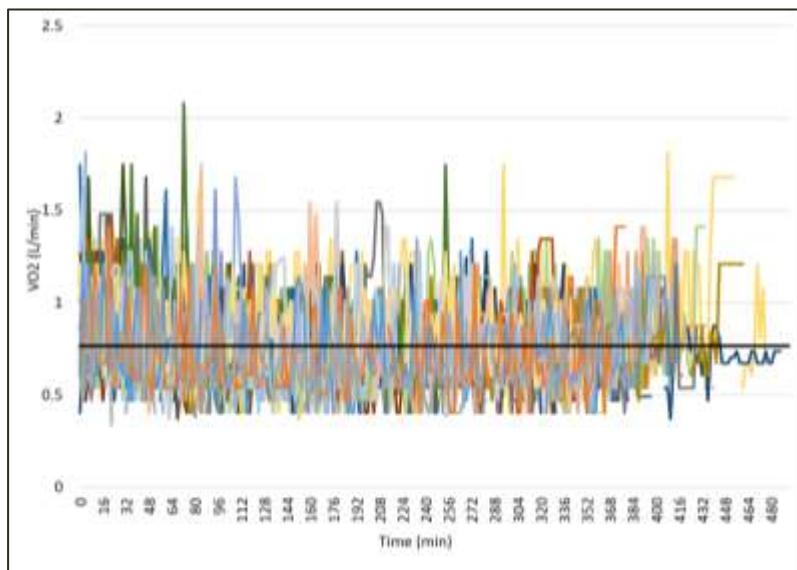


## Background

### Astronaut aerobic characteristics and in-mission $\text{VO}_2$ activity data

- All crewmember height range: 146.6 cm to 194.6 cm (58.5 inches to 76.6 inches)
- All crewmember weight mean: 72.4kg/170 lbs std deviation 8kg/17.7 lbs Range, 95 percentile 90.6 kg/199 lbs

#### $\text{VO}_2$ during ISS EVAs (microgravity)



O-G EVA MET rates from EVAs 15-46. Average  $\text{VO}_2 = 0.77$  L/min. Each colored line represents  $\text{VO}_2$  levels (y axis) across time (x axis). Average  $\text{VO}_2$  for all EVAs (black line) was approximately 10 ml/kg/min.

#### Lunar Surface/Apollo $\text{VO}_2$ Data (1/6<sup>th</sup> g)

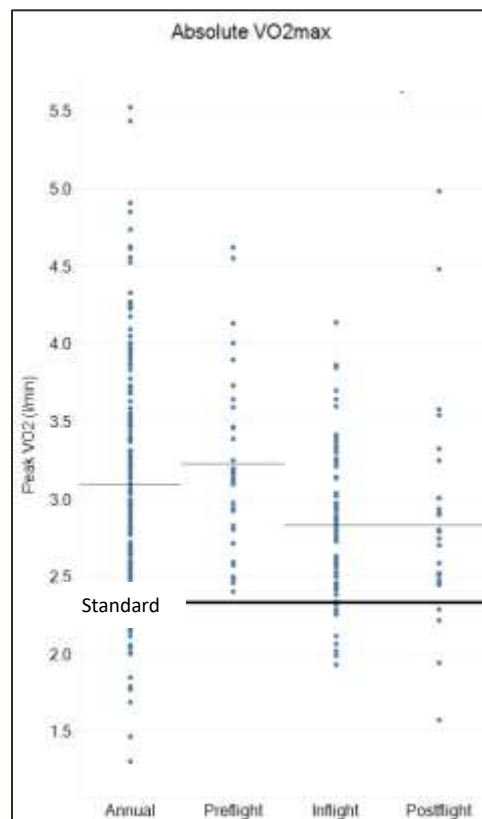
$\text{VO}_2$	ALSEP Deployment	Geology	Overhead	Rover
$\text{VO}_2$ (L/min)				
Avg	0.81	0.81	0.90	0.41
Max	1.01	1.17	1.01	0.58
$\text{VO}_2$ (ml/kg/min) for 80 kg crewmember				
Avg	10.17	10.17	11.25	5.13
Max	12.58	14.63	12.63	7.21

Apollo Lunar Surface Experiments Package (ALSEP)  
Geology (utilizing tools for collecting geological samples)  
Overhead activities (ingressing and egressing the vehicle)  
Rover (driving and maneuvering extraterrestrial surface vehicle)

From Biomedical Results of Apollo (1975)

<https://ntrs.nasa.gov/citations/19760005580>

#### ISS Crewmember Data

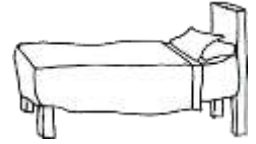


Crewmember data from ISS increments 20-32, 28-51, 37-56

From: HSRB Proposed Muscle Strength and Aerobic Capacity-Related updates to NASA-STD-3001 Standard Recommendation (2018)

Note: To Convert l/min to ml/(min/kg):  
(l/min x 1000 ml/min)/body weight in kg  
Example: 1.17 x 1000ml/min/80 kg = 14.63

In mission activities require relatively low  $\text{VO}_2$  levels but crewmember initial fitness level and in mission projected losses need to be accounted for to ensure successful mission activities.



## Background

### Bedrest Studies

Research utilizing head-down bedrest (HDBR) methods have been implemented extensively to gather physiological data that can be translated to spaceflight practices. These methods are the closest terrestrially based research strategies that simulate the physiological changes the human body endures from the elimination of gravity during spaceflight, including fluid shifts to the head and upper torso, BMD loss, changes to the musculoskeletal system, cardiovascular changes, and sensorimotor degradation\*. Subjects are placed on bedrest with specific degree of head-down tilt for short to long durations during which time countermeasures including exercise protocols are used to mitigate bone loss, strength, and aerobic changes.

*\*(Belavy et al., 2010; Cromwell et al., 2019; Hargens et al., 2006; Pavy-Le Traon et al., 2007; Schneider et al., 2009; Stuempfle & Drury, 2007)*



NASA Bedrest Treadmill

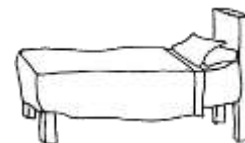


NASA Bedrest Strength Horizontal Squat Device

### Benefits of exercise during bedrest studies

NASA uses exercise during bedrest as an analog to see how well humans benefit from and/or tolerate exercise during microgravity/spaceflight.

- Short duration bedrest without exercise may show comparable decrements to spaceflight and provides insight into possible magnitude of decrements due to microgravity exposure.
- Significant changes in knee extension strength and aerobic capacity occur early.
- Short duration bedrest without exercise may show comparable decrements to spaceflight.



## Background

### Integrated resistance and aerobic exercise protects fitness during 14-day bed rest

(Ploutz-Snyder et al., 2014)

- Evaluated the effectiveness of exercise using ISS-like hardware during short duration bedrest to maintain cardiovascular and muscular fitness during 14 days of bedrest.
- Nine subjects participated in 14-21 days of pre-bedrest training, 14 days of bedrest + exercise, and 7 days of ambulatory recovery.
- Aerobic- $\dot{V}O_{2peak}$ , ventilatory threshold (VT), and isokinetic/leg press tests performed before/after bedrest to evaluate cardiorespiratory and muscular functions.
- Subjects exercised 6 days/week, 3 days of resistance and 6 days aerobic.
- Used vertical treadmill, supine cycle ergometer, and horizontal exercise fixture.
- High-intensity interval and continuous aerobic exercise were performed on alternating days.
- Training based on review of effective training programs for skeletal, muscle, bone, and cardiovascular health.
- Exercise alone in this spaceflight analog can preserve cardiorespiratory and muscular fitness for a 14-day period.
- This test was followed by a 70-day bedrest study with similar conditions.

### Bedrest effects of exercise on aerobic capacity

	$\dot{V}O_{2peak}$ (L·min <sup>-1</sup> )	$\dot{V}CO_{2peak}$ (L·min <sup>-1</sup> )	$\dot{V}_E$ (L·min <sup>-1</sup> )	Test Time (min)	Peak Workload (W)	VT (L·min <sup>-1</sup> )
Screening	2.8 ± 0.27	3.5 ± 0.26	112.4 ± 5.28	11.1 ± 0.80	232 ± 19	1.9 ± 0.19
BR - 14	3.0 ± 0.26*	3.5 ± 0.23	114.9 ± 5.92	11.1 ± 0.79	246 ± 19	1.9 ± 0.15
BR + 0	3.2 ± 0.21*	3.7 ± 0.22	119.2 ± 6.17	11.6 ± 0.69	257 ± 17*	ND
BR + 5	3.2 ± 0.19*	3.8 ± 0.21*	124.9 ± 6.74*	12.1 ± 0.61***	268 ± 16***	2.1 ± 0.19***

### Bedrest effects of exercise on muscle size

Volume (cm <sup>3</sup> )	Thigh		Calf		Total	
	BR1	BR14	BR1	BR14	BR1	BR14
SAT, n = 8	425 ± 322	447 ± 309	117 ± 121	121 ± 92	542 ± 405	568 ± 387
IMAT, n = 8	117 ± 29	117 ± 28	90 ± 50	84 ± 44	207 ± 75	201 ± 66
Muscle	1757 ± 222	1771 ± 240	622 ± 195	628 ± 202	2379 ± 318	2399 ± 336

BR = bedrest;  $\dot{V}O_{2peak}$  = oxygen consumption;  $\dot{V}CO_{2peak}$  = carbon dioxide production;  $\dot{V}_E$  = rate of ventilation; VT = ventilatory threshold SAT = skeletal muscle, subcutaneous; IMAT = intermuscular adipose tissue

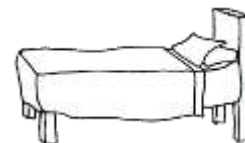


NASA bedrest exercise equipment  
Right: Centrifuge used at the German Aerospace Center's "envihab" facility to study simulated microgravity state.  
Left: Horizontal exercise fixture.



This study demonstrates the potential benefit of high-load resistance exercise coupled with high-intensity interval training using conventional equipment in a spaceflight analog. Results included increased or maintained aerobic and muscle performance immediately after bed rest. Previous bed rest study showed 14% decline after 10-day bed rest (no exercise).





## Background

### Exercise Training Mitigates Multisystem Deconditioning during Bed Rest

(Ploutz-Snyder et al., 2014)

This study evaluated safety and effectiveness of aerobic and resistance exercise using ISS-like exercise capability in the spaceflight analog of bedrest. 34 subjects completed 70 days of 6-degree head down tilt. The exercise countermeasures consisted of high-intensity interval and continuous aerobic training combined with resistive strength training 6 days per week. High-intensity interval aerobic exercise was completed every other day alternating with continuous aerobic exercise performed along with resistance exercise separated by 4–6 hours.



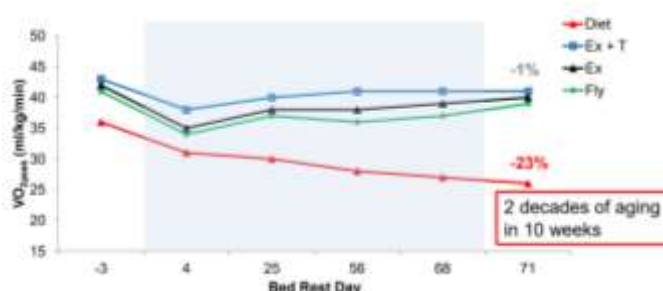
Specialized treadmill (left) was custom built to allow subjects to remain in the supine position during exercise, continuous aerobic exercise was performed on a supine electronic cycle ergometer (right)



	CONT		EX		EX+T		FLY	
	BR - 5	BR + 0	BR - 5	BR + 0	BR - 5	BR + 0	BR - 5	BR + 0
$\dot{V}O_{2peak}$ , L·min <sup>-1</sup>	2.9 ± 0.6	2.2 ± 0.4	3.2 ± 0.6	3.2 ± 0.6 *	3.2 ± 0.5	3.1 ± 0.4 *	3.2 ± 0.7	3.0 ± 0.6 *
VT, L·min <sup>-1</sup>	2.0 ± 0.4	1.5 ± 0.3	2.0 ± 0.3	2.0 ± 0.4 *	2.1 ± 0.4	2.0 ± 0.4 *	2.0 ± 0.5	2.0 ± 0.5 *
Peak workload, W	242 ± 53	181 ± 42	261 ± 47	265 ± 53 *	267 ± 28	264 ± 25 *	272 ± 53	264 ± 32 *
Peak HR, bpm	189 ± 7	188 ± 10	177 ± 8	176 ± 10	178 ± 14	178 ± 9	182 ± 5	186 ± 8

CONT = no exercise, EX=traditional exercise equipment, EX+T=traditional ISS equipment + testosterone, FLY= single flywheel equipment. BR-5 is 5 days before bedrest, BR+0 is day bedrest is complete

### Results: Cardiorespiratory Fitness

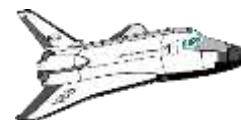


### 70 Day Bedrest Intervention groups

- Diet - Control Group: no exercise
- Ex + T - Traditional ISS equipment + testosterone
- Ex - Traditional ISS exercise equipment
- FLY - Single Flywheel rowing and resistance exercise device

- 1) The exercise protocol mitigated bed rest induced muscle and cardiac deconditioning regardless of exercise device used.
- 2) Peak aerobic capacity was maintained from pre to post bed rest in all exercise groups compared to a 10% decline in controlled group.
- 3) FLY training was effective in mitigating multisystem deconditioning relative to the exercise performed on traditional (e.g., resistance machines, treadmill, cycle ergometer) exercise equipment.





## Background

### Aerobic Exercise on Space Shuttle: 6-15 days

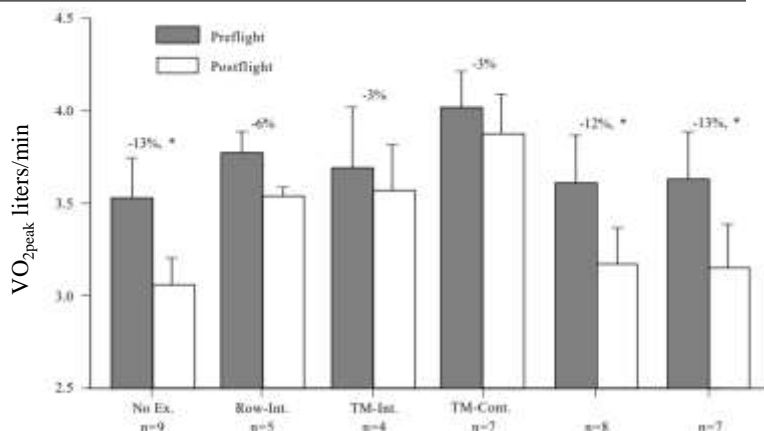
**Extended Duration Orbiter Medical Project Functional Performance Evaluation** Greenisen et al., (1999)

Studies were performed on the Space Shuttle to evaluate the usefulness of sub-maximal aerobic exercise during flight in reducing the severity of postflight deconditioning. One of the studies (below) tested effects of exercise using different modalities including treadmill, rower, and cycle on aerobic deconditioning compared to no exercise.

*Flight duration and exercise volume*

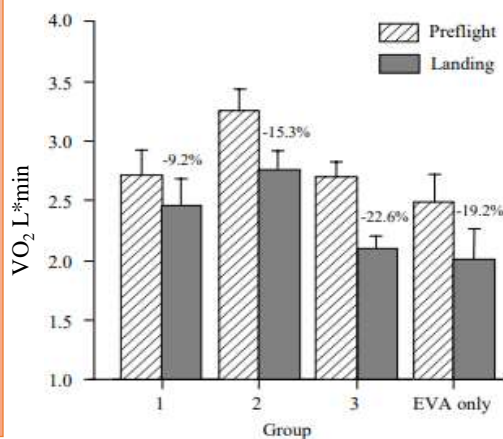
Exercise Modality	Flight Duration, days	"Exercise Vol" Before Flight	"Exercise Vol" During Flight	"Exercise Vol" During/Before
No exercise	10	8.7 ± 1.9	NA	NA
Cycle	16	12.1* ± 3.2	20,737 ± 19,429	97
Rower or treadmill	9	7 ± 1.7	17,799 ± 8,097	71
Treadmill, continuous	7	8.6 ± 1.1	15,858 ± 6,993	107

Study evaluated pre-flight to post-flight effect of exercise on 40 crew comparing exercise modalities (rowing, treadmill, and cycle). All modalities had some protective effects (right).



#### Results:

Subjects who exercised three or more times per week during flight, at a HR >70% of their age-predicted maximum HR and for more than 20 minutes per session, experienced smaller decrements in  $VO_2$  at test termination on landing day than subjects who exercised less frequently or at lower intensities.



Study evaluated effect of exercise duration and intensity on 25 subjects (left).

- Group 1 (n=11): Exercised >3x/week. HR >70% age-predicted, ≥20 min/session ("regular" exercise group)
- Group 2 (n=10): Exercised >3x/week. HR <70% age-predicted, ≥20 min/session ("low intensity" exercise group)
- Group 3 (n=14): Exercised <3x/week. HR and min/session variable ("minimal" exercise group)
- EVA Only (n=4): Subjects performed EVAs. Minimal other exercise performed during flight (Hubble mission)

#### Health Technical Requirement

##### 4.1.3 In-Mission Aerobic Capacity

[V1 4003] The in-mission aerobic capacity **shall** be maintained, either through countermeasures or work performance, **at or above 80%** of the pre-mission capacity determined by either direct or indirect measures. From NASA-STD-3001 Vol 1, Rev C



## Reference Data

### ISS Preflight Training Exercise Prescription – 180 Days

- Prepare for flight
  - Muscle Conditioning (strength, endurance, flexibility, power, coordination, and stamina)
  - Aerobic Fitness
- Preflight training begins approximately 2 years before a scheduled launch
  - Familiarize astronauts with inflight exercise and hardware operation
  - Teach proper safety and technique

#### Example preflight periodization workout

Cycle/Phase	Sets	Reps
Preparation/Hypertrophy	3-4	10-12
Basic Strength	3-4	8-10
Strength & Power	4	4-6
Peaking Power	4	1-3
Stamina	3-4	15+

*Adapted from: Physical Training for Long-Duration Spaceflight (Loehr et al., 2015)*

### Inflight Training Exercise Prescription (Long-Duration Missions ~180 days/ISS)

Maintain crew health and fitness

- Protect functionality and capability
- Minimize losses: Strength, endurance, flexibility, power, coordination, stamina, aerobic fitness, and bone
- Injury Prevention

#### Inflight Training Time Prescriptions

##### **Metabolic:**

Approximately 30 minutes of interval or steady-state exercise

##### **Resistive/Strength:**

30-60 minutes load-bearing training



*Astronaut Chris Cassidy using the Advanced Resistive Exercise Device (ARED)*

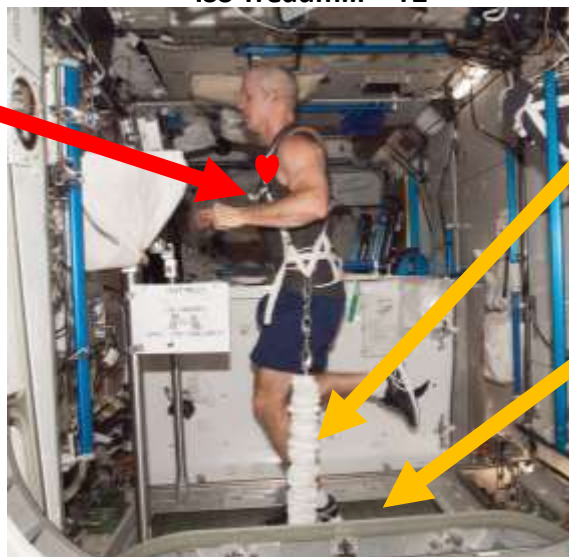


## Application

### Aerobic Exercise in Space - ISS Long Duration ~ 180 Days

Aerobic training on ISS consists of interval or continuous steady state exercise on either Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS) or second-generation treadmill (T2). CEVIS protocols were developed using the pre-flight  $VO_{2peak}$  test with prescribed work rates between 70-100%  $VO_{2peak}$ . T2 protocols were based on pre-flight training and prescribed at 70-100% HRmax. The following data was obtained during ISS increments 26S-50S (April 2011 – September 2017). Forty-six astronauts (37 males, 9 females; age:  $46.8 \pm 6.1$  years, height:  $176 \pm 7.1$  cm, weight:  $79.2 \pm 9.9$  kg [mean  $\pm$  SD]) were assigned to missions of  $178 \pm 48$  d. Ten (22%) astronauts had previously completed long-duration ISS missions. The following data is based on “Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts”, Scott, J. et al. (2023).

#### ISS Treadmill – T2



##### Heart Rate

131 bpm average  
Peak 162 bpm

##### Heart Rate

>70 % peak heart rate  
69%  
> 90% peak heart rate  
11%

##### Frequency

84 (range 59-109)/178 days  
47% of total days on orbit

##### Loading System

Average load 117 lbs  
Range 107- 127 lbs  
68% body mass loading

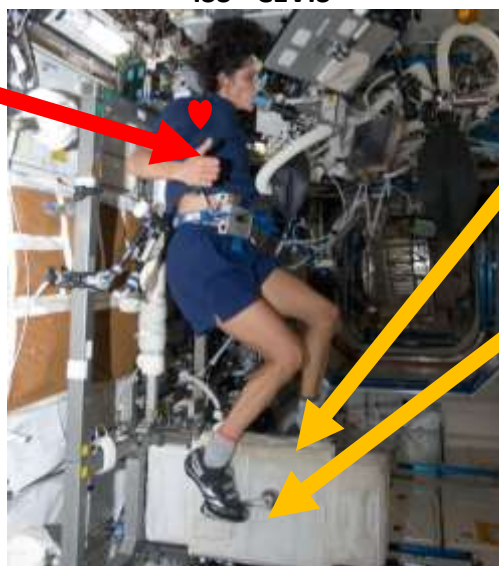
##### Speed mph

All 7 mph  $\pm$  1  
Peak 8 mph  $\pm$  1

##### Exercise Session Duration

27 minutes (range 23-29 min)

#### ISS - CEVIS



##### Heart Rate

135 bpm average  
Peak 163 bpm

##### Heart Rate

>70 % peak heart rate  
76%  
> 90% peak heart rate  
13%

##### Frequency

65 (range 47-76)/178 days  
37% of total days on orbit

##### Load (W)

Average load 137 W  
Peak 191 W

##### Speed rpm

All 78 -7/+19  
Peak 92  $\pm$  5

##### Exercise Session Duration

26 minutes (range 23-29 min)

\*\*The % maximum HR parameter was calculated as the average HR of the individual exercise sessions for that crew member, divided by the crew member's HRmax (determined preflight as part of Peak Aerobic performance testing), then multiplied by 100%.

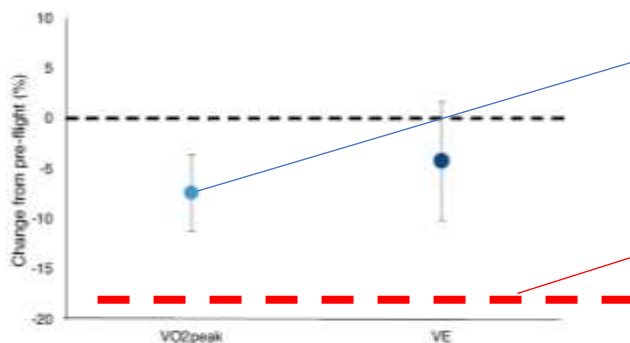




## Background

### Aerobic Exercise in Space ISS Long Duration ~ 180 Days Physiological Outcomes

Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts (Scott et al., 2023). Evaluation of the effects of ISS exercise countermeasures on multisystem function using latest exercise (T2, ARED, CEVIS) devices and exercise prescription processes with average 600 min/week/crewmember; and estimated the proportion of astronauts that would experience performance-limiting deconditioning including cardiorespiratory (aerobic), bone, and body composition. Testing was performed on NASA and international astronauts from April 2011-Sept 2017: 46 missions min. of 178 days, all meeting standard physiologic tests prior to flight.



After 178 days, crewmembers in this study lost on average 7% of their VO<sub>2peak</sub>

#### Health Technical Requirement

##### 4.1.3 In-Mission Aerobic Capacity

[V1 4003] The in-mission aerobic capacity **shall** be maintained, either through countermeasures or work performance, **at or above 80%** of the pre-mission capacity determined by either direct or indirect measures.

From NASA-STD-3001 Vol 1, Rev C

Crew data from 2012-2022 found that 12-21% of crewmembers fall below the -20% requirement during in-flight time points. 20% or greater aerobic reduction is associated with significant performance decrements in ground based analog study that evaluated simulated EVA and egress task performance.

Table 1. Inflight Aerobic and Resistance Exercise Training.

	Aerobic Exercise	
	CEVIS	T2
Sessions, number	65 (47, 76)	84 (59, 109)
*Exercise time/session, mins	26 (23, 29)	27 (23, 29)
Heart Rate, beats/min		
Average	135 (128, 141)	131 (121, 137)
Peak	158 (150, 163)	153 (144, 162)
% time in heart rate zone		
Above 70% peak heart rate	76 (65, 92)	69 (54, 81)
Above 90% peak heart rate	13 (6, 27)	11 (4, 24)
Speed, rpm (CEVIS) or mph (T2)		
All	78 (71, 97)	7 (6, 7)
Peak	92 (88, 97)	8 (7, 9)
Load, W (CEVIS) or lb (T2)		
All	137 (123, 153)	117 (107, 127)
Peak	191 (173, 223)	N/A
Repetitions, number	N/A	N/A
Load volume	5013 (3864, 5763)	2909 (2531, 3279)

Estimated in-mission aerobic capacity declines and required in-mission aerobic capacity levels should be considered when setting the pre-mission aerobic capacity requirement. See table below from [V1 4001] Microgravity EVA Aerobic Capacity from NASA-STD-3001 Vol 1, Rev C for an example.

Table 4.1-1— Pre-mission VO<sub>2max</sub> Recommendations and Required Minimum In-mission VO<sub>2max</sub>

Example Destination	In-Mission VO <sub>2max</sub>	VO <sub>2max</sub>	
		Pre-Mission VO <sub>2max</sub> Recommendation (assuming an in-mission 15% decline)	Pre-mission VO <sub>2max</sub> Recommendation (assuming an in-mission 25% decline)
ISS	32.9 ml/min/kg	38.7 ml/min/kg	43.8 ml/min/kg

### Post Mission Reconditioning

Crewmembers participate in a reconditioning program post-landing. After 30 days, crewmembers regain their pre-flight baseline VO<sub>2peak</sub> values.

Endpoint	Change pre-flight to R+1	Change pre-flight to R+7	Change pre-flight to R+30
Total mass		-0.13 (-1.40, 0.86)	
Fat mass		-0.34 (-6.06, 1.34)	
Lean mass		0.26 (-0.59, 1.55)	
VO <sub>2peak</sub>	-1.53 (-11.21, -3.55)	-1.15 (-8.42, -2.66)	0.13 (-2.35, 3.58)
Ventilation	-0.48 (-10.15, 1.72)	-0.08 (-5.73, 4.25)	-0.33 (-8.10, 2.35)
Ventilatory threshold	0.20 (-4.57, 7.66)	-0.08 (-6.28, 5.14)	0.09 (-6.46, 7.81)



## Background

### Muscle Strength & Resistive Exercise

Exposure to weightlessness can cause muscle deconditioning as a result of chronic disuse, insufficient functional loads, reduced muscle mass, volume, and performance. Crewmember muscle strength is important for the completion of necessary tasks including in-flight activities, EVAs, successful egress of the vehicle, and assisting an incapacitated crewmember. Wearing a spacesuit adds additional strength demands. Exercise is one of the most important countermeasures used to minimize loss of strength. Goals for in-flight training include maintaining crew health and fitness and protecting functionality and EVA capability while minimizing losses of strength, endurance, flexibility, power, aerobic fitness, and injury protection.

**Muscle strength** is measured as **torque** and **endurance**

**Torque** is the force that drives biomechanical movement.

**Total work** is a measure of muscle **endurance**.

Concentric contractions - muscles shorten and generate force. Eccentric contractions - muscles lengthen in response to force. Isometric contractions - generate force without changing shape.

Isokinetic testing measures strength at concentric, eccentric, and isometric modes.

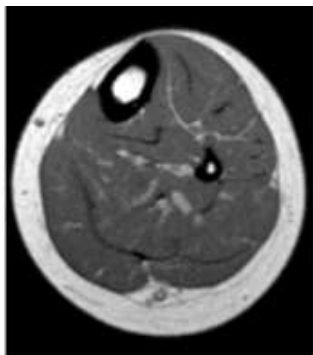
Isokinetic testing provides a baseline of muscle strength and endurance in select muscle groups.

Crewmembers have an isokinetic assessment before and after flight per NASA AMMERD 6.1

Measurements can be used for evaluation of in-flight countermeasures and post-flight rehabilitation.



Pre-flight muscle evaluation leg press tests maximal isometric force and power/endurance. Knee extension tests force control and neuromuscular drive.



**MRI** - Muscles can be evaluated by MRI which shows reductions in muscle size. Loss of muscle can be directly related to movement control – less mass available/less tension produced when muscles are maximally activated and lower functional performance

*Muscle size can be monitored for atrophy in-flight using a guided ultrasound device (right)*



NASA Astronaut Strength, Conditioning, and Rehabilitation Specialists (ACERS) monitor crew fitness in-flight and develop exercise prescriptions based on crew ability and performance. Crew data is monitored from the ground, including physiologic markers and crew performance such as time and intensity of exercise performed. Strength exercise prescriptions depend on equipment available

Functional Performance Evaluation Michael C. Greenisen, Judith C. Hayes, Steven F. Siconolfi, and Alan D. Moore of the Johnson Space Center, Houston, TX

NASA Office of the Chief Health & Medical Officer (OCHMO)

This Technical Brief is derived from NASA-STD-3001 and is for reference only.

It does not supersede or waive existing Agency, Program, or Contract requirements.

10/02/2023

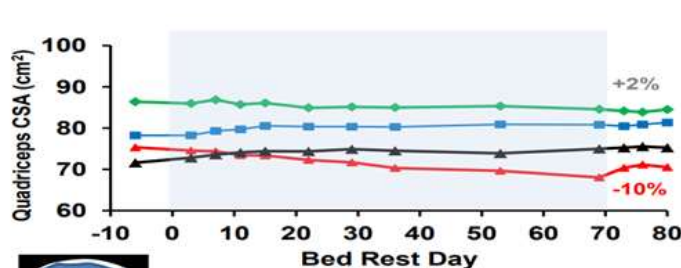


## Background

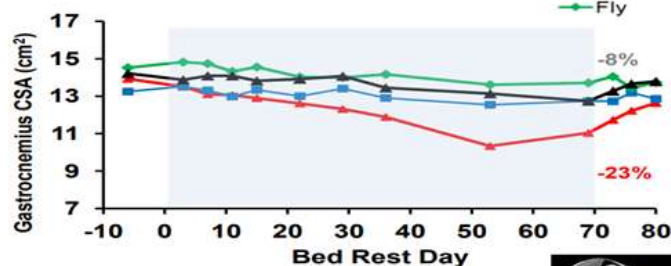
### Integrated resistance and aerobic exercise protects fitness during 70-days bed rest

This study evaluated safety and effectiveness of aerobic and resistance exercise using ISS-like exercise capability in the spaceflight analog of bed rest. 34 subjects completed 70 days of 6-degree head down tilt. The exercise countermeasure consisted of high-intensity interval and continuous aerobic training combined with resistive strength training 6 d·wk<sup>-1</sup>. High-intensity interval aerobic exercise was completed every other day alternating with continuous aerobic exercise performed along with resistance exercise separated by 4–6 h.

## Results: Leg Muscle Mass



Muscle size is significantly maintained by exercise.



Study Length		Variable	Control (n=9)	Flywheel (n=8)
Ploutz-Snyder 2018	70	Isokinetic Knee Extension (60°; Nm)	-23%	-13%
		Leg Press Max Isometric Force (N)	-16%	-7%
		Leg Press Max Power (W)	-21%	-8%
		Isokinetic Plantar Flexion (30°; Nm)	-29%	-4%
		VO2peak (L/min)	-24%	-6%

	CONT		EX		ExT		FLY	
	BR - 5	BR + 0	BR - 5	BR + 0	BR - 5	BR + 0	BR - 5	BR + 0
Quadriceps, cm <sup>2</sup>	75.3 ± 17.7	81.1 ± 5.9	78.7 ± 10.7	81.1 ± 12.3 <sup>*</sup>	71.6 ± 11.6	75.0 ± 12.6 <sup>*</sup>	86.4 ± 16.0	84.6 ± 18.4 <sup>***</sup>
Hamstrings, cm <sup>2</sup>	35.6 ± 7.2	32.5 ± 4.2	32.5 ± 4.3	32.8 ± 5.4 <sup>*</sup>	32.3 ± 4.9	32.0 ± 5.0 <sup>*</sup>	38.0 ± 9.4	35.9 ± 7.9

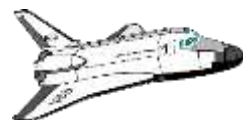
Resistance exercise was performed using a horizontal leg press. Custom-built flywheel device was used for aerobic and resistive strength exercise.

	CONT		EX		ExT		FLY	
	BR - 5	BR + 0	BR - 5	BR + 0	BR - 5	BR + 0	BR - 5	BR + 0
Leg press MIF, N	1975 ± 578	1657 ± 728	2070 ± 406	1965 ± 533	1857 ± 300	1768 ± 258	2367 ± 633	2196 ± 587
Leg press total work, J	8616 ± 1942	6714 ± 1241	8644 ± 2377	8162 ± 2450 <sup>*</sup>	8571 ± 1744	8137 ± 1744 <sup>*</sup>	10130 ± 2351	9409 ± 2228 <sup>*</sup>
Leg press max power, W	1836 ± 430	1445 ± 342	1943 ± 436	1830 ± 581 <sup>*</sup>	1791 ± 249	1724 ± 316 <sup>*</sup>	2377 ± 721	2194 ± 609
Isokinetic KE 60	191.4 ± 45.0	147.7 ± 42.0	201.0 ± 59.6	184.9 ± 64.2 <sup>*</sup>	206.1 ± 32.3	197.7 ± 26.8 <sup>*</sup>	212.7 ± 36.6	185.0 ± 32.5 <sup>***</sup>
Isokinetic PF 30	126.3 ± 32.0	89.3 ± 16.5	129.5 ± 39.4	116.3 ± 31.0	136.6 ± 20.5	118.9 ± 22.3	109.6 ± 19.0	104.8 ± 23.6 <sup>*</sup>
Vertical jump max height, cm	42.5 ± 7.0	32 ± 5.8	43.6 ± 5.4	41.4 ± 5.5 <sup>*</sup>	44.3 ± 8.2	39.3 ± 6.8	45.5 ± 4.3	44 ± 5.2 <sup>*</sup>
Vertical jump max power, W·kg <sup>-1</sup>	44.6 ± 5.8	36.5 ± 4	45.5 ± 5.8	43.8 ± 6.7 <sup>*</sup>	46.0 ± 6.9	44.1 ± 8 <sup>*</sup>	50.3 ± 6.2	49.5 ± 6.8 <sup>*</sup>

Significant benefits shown from all exercise groups compared to non-exercise (cont) group. All exercise groups were observed for leg press total work, isokinetic upper and lower leg strength, and vertical jump power and maximal jump height.

BR-5 is measured 5 days before flight, BR+0 measured day bedrest is complete.

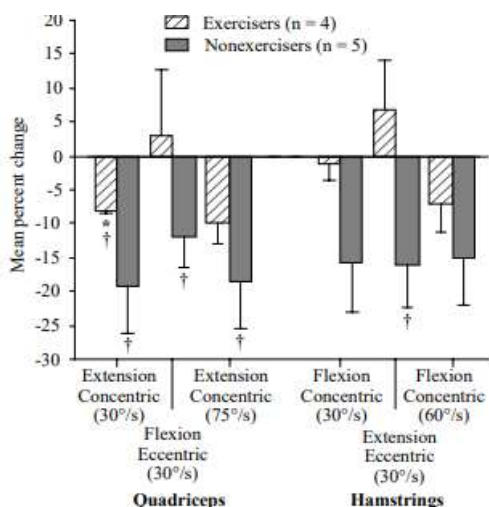




## Application

### Extended Duration Orbiter Medical Project Functional Performance Evaluation Greenisen et al. (1999)

**Short-Duration** Studies were performed on Shuttle crewmembers to evaluate the usefulness of sub-maximal skeletal muscle and endurance exercise during flight to optimize crew ability to complete mission tasks including those essential to entry, landing, and crew egress. One study evaluated functional changes in peak torque and muscle endurance before/after flight, one defined the morphologic and biochemical effects of spaceflight on skeletal muscle fibers, a third used MRI to test for leg muscle atrophy.



**Study 477 and 617** evaluated functional changes in concentric/eccentric strength (peak torque) and endurance (workload) of the trunk, upper, and lower limbs.

- Shuttle missions 5-13 days, pre-training began L-30
- Exercisers had protocols of continuous and interval training, treadmill prescriptions 60-85% of pre-flight  $\text{VO}_{2\text{max}}$

#### Results

- Torque decreased in back and abdomen, quadriceps 15% hamstrings 12%
- Total work decreased in quadriceps at R+0, small difference in endurance at R+7
- Exercisers had greater maintenance of leg strength (left)
- Both exercisers and non-exercisers lost strength in abdomen and trunk suggesting that treadmill exercise may best preserve muscle integrity to muscles exercised.

**Study 475** defined the morphologic and biochemical effects of spaceflight on skeletal muscle fibers.

- Biopsies taken 21 days before flight and on landing day
- 8 crew 3-5 day mission and 5-11 day missions
- Tested Type 1 slow-twitch fibers (endurance activities), and type 2- fast twitch (quick powerful movements)

#### Results

- Cross section area (CSA) showed 15% loss of type 1 fibers and 22% decrease of type 2 fibers after flight

**Study 606** quantified changes in size, water, lipid composition, and leg muscles after spaceflight.

- 8 crew 5-7 days and 3-9 days
- Tested MRI of leg L-30, L-16, R+2, R+7
- MRI scan of leg (soleus and gastrocnemius muscles)
- CSA evaluated to assess muscle atrophy

#### Results

- 5.8% lost in the soleus, 4.0% lost in the gastrocnemius, 4.3% total
- Loss represents atrophy (loss of muscle mass)

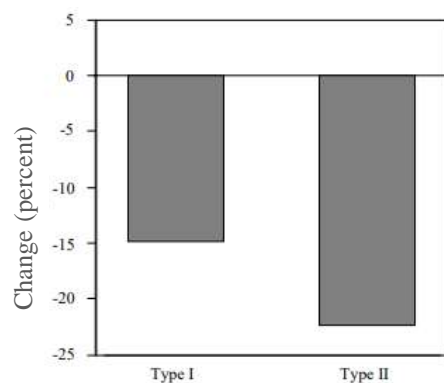
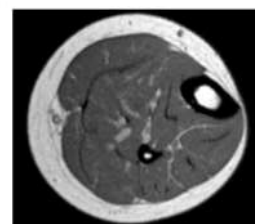


Figure 3-6 Preflight vs. postflight, percent change by skeletal muscle fiber type of the vastus lateralis (n=8).



MRI image

Functional Performance Evaluation Michael C. Greenisen, Judith C. Hayes, Steven F. Siconolfi, and Alan D. Moore



## Application

### Resistive/Strength Exercise in Space – ISS Long Duration ~180 Days

For resistance exercise, total volume was calculated for each subject for the categories of squat, heel raise, and deadlift exercises utilizing the ARED (600lb. total resistance), then normalized to mission duration (total volume/mission duration in days). Warmup exercises were not included in the data set. The 3 exercise categories included the following variations: “squat”: back squat, single leg squat, sumo squat; “heel raise”: heel raise and single leg heel raise; “deadlift”: deadlift, Romanian deadlift, and sumo deadlift, and bench press. For each exercise category, total volume was calculated for each subject by summing the volume (load x reps) across the entire mission. In addition, average load (kg), average relative load (kg/kg bodyweight<sup>-1</sup>), average repetitions per session, and average repetitions per week were calculated for each subject for the 3 exercise categories. The following data is based on the “Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts”, Scott, J. et al. (2023).

#### ARED – Bench Press



**Load**  
Average load 122 lbs  
Range 98 – 153 lb  
**Peak Load**  
131 lbs  
Range 102 – 160 lbs  
**Load Volume**  
4928 lbs  
**Sessions**  
N/A  
**Repetitions**  
44 (range 38 - 81)/178 days

#### ARED - Squat



**Load**  
Average load 181 lbs  
Range 150 – 223 lbs  
**Peak Load**  
229 lbs  
Range 194 – 270 lbs  
**Load Volume**  
31,659  
**Sessions**  
117  
Range (78-148)  
**Repetitions**  
189 (range 135-223)/178 days

#### ARED - Heel Raise



**Load**  
Average load 239 lbs  
Range 198 – 293 lbs  
**Peak Load**  
249 lbs  
Range 202 – 306 lbs  
**Load Volume**  
45,855 lbs  
**Sessions**  
85  
Range 65 to 105  
**Repetitions**  
207 (range 131-256)/178 days

#### ARED - Deadlift



**Load**  
Average load 192 lbs  
Range 156 - 215 lbs  
**Peak Load**  
220 lbs  
Range 180 – 248 lbs  
**Load Volume**  
38,300 lbs  
**Sessions**  
121  
Range (82 to 146)  
**Repetitions**  
230 (range 177-313)/178 days

\*All Crewmember Height range: 146.6 cm to 194.6 cm (58.5 inches to 76.6 inches). All crew weight mean:

72.4kg/170 lbs std deviation 8kg/17.7 lbs Range, 95 percentile 90.6 kg/199 lbs

\*\*The % maximum HR parameter was calculated as the average HR of the individual exercise sessions for that crewmember, divided by the crewmember’s HRmax (determined pre-flight as part of Peak Aerobic performance testing), then multiplied by 100%.

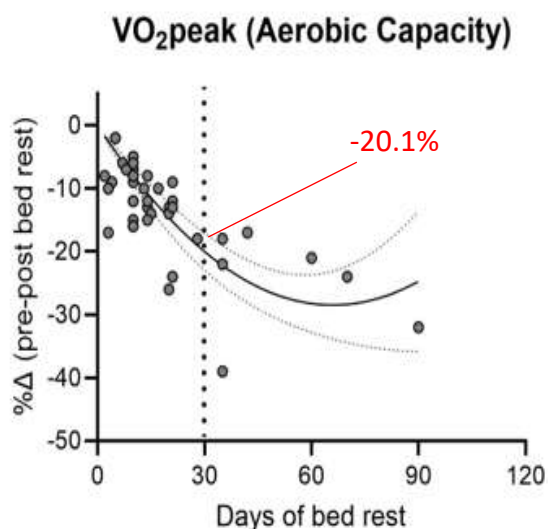


## Background

### Summary of Bedrest Data with No Exercise

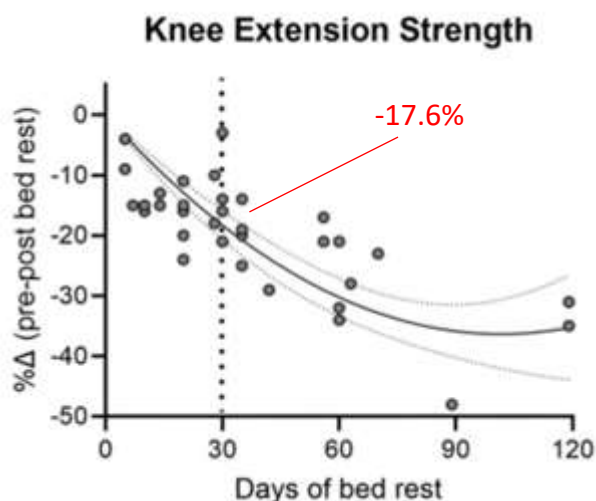
The following graphs summarize bedrest data collected over studies conducted between 1 to 120 days. The bedrest data in combination with the flight data presented in the following slide is used to inform exercise requirements and protocols for missions of various durations.

#### *Effect of bedrest on aerobic capacity without exercise*



**Aerobic Capacity:** Relationship between change in aerobic capacity ( $VO_{2peak}$ ) and bed rest duration in control participants with no exercise. Individual points on the scatterplot indicate aggregated data from individual studies employing 6° head down tilt and horizontal bed rest with no exercise (n=443 subjects; 48 data points). Some studies had measures at multiple times throughout bed rest or employed additional research interventions – each of these are presented as an individual dot at the corresponding timepoint. Some points for individual studies may be overlayed by other studies. The estimated 30-day decrement in knee extension strength is -20.1%.

#### *Effect of bedrest on strength without exercise*



**Knee extension:** Relationship between change in knee extension strength (from pre-post bed rest) and duration of bed rest, in control participants with no exercise. Individual points on the scatterplot indicate aggregated data from individual studies employing 6° head down tilt and horizontal bed rest with no exercise (n=283 subjects; 34 data points). Some studies had measures at multiple times throughout bed rest or employed additional research interventions – each of these are presented as an individual dot at the corresponding timepoint. Some points for individual studies may be overlayed by other studies. The estimated 30-day decrement in knee extension strength is -17.6%.

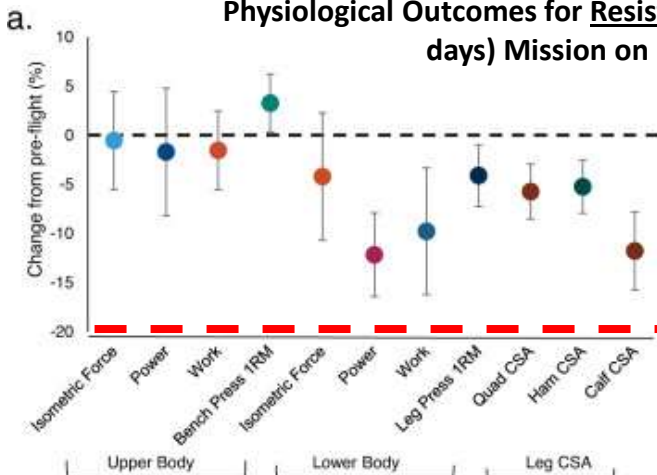
Data from: Strock N, Varanoske A, Spector E, Frisco D, Young M, Prejean B, Fincke R, Marshall-Goebel (2023) Exercise Requirements for Gateway and Orion: Human Physiology, Performance, Protection, and Operations (H-3PO) Laboratory Review of Muscle and Aerobic Outcomes in relation to Exercise Prescription Design.





## Background

### Physiological Outcomes for Resistive Exercise on Long Duration (178 days) Mission on ISS Scott et al., 2019



#### Health Technical Requirement 4.6.2 In-Mission Skeletal Muscle Strength

[V1 4024] Countermeasures **shall** maintain in-mission skeletal muscle strength **at or above 80%** of baseline values. *From NASA-STD-3001 Vol 1, Rev C*

#### Inflight resistance exercise training

	Aerobic Exercise			
	CEVIS	T2	Squat	Bench Press
Sessions, number	65 (47, 76)	84 (59, 109)	117 (78, 148)	
All	192 (156, 215)	239 (198, 293)	181 (150, 223)	122 (98, 153)
Peak	220 (180, 248)	249 (202, 306)	229 (194, 270)	131 (102, 160)
Repetitions, number	230 (177, 313)	207 (131, 256)	189 (135, 233)	44 (38, 81)
Load volume	38,300 (28,770, 61,681)	45,855 (32,410, 67,364)	31,659 (22,745, 46,150)	4928 (4601, 10,311)

### Post-Mission Reconditioning

Crewmembers participate in a reconditioning program post-landing. After 30 days post-landing, crewmembers regain their pre-flight baseline force, work, and power values.

Endpoint	Change pre-flight to R+1	Change pre-flight to R+7	Change pre-flight to R+30
Leg Press Force	-0.60 (-10.70, 2.27)	-0.23 (-7.57, 4.39)	0.26 (-3.99, 7.62)
Leg Press Power	-2.36 (-16.43, -7.92)	-1.90 (-13.74, -5.81)	-0.77 (-8.82, 0.84)
Leg Press Work	-1.30 (-16.23, -3.34)	-0.68 (-11.61, 1.43)	-0.04 (-7.36, 6.76)
Leg Press 1-RM	-0.60 (-7.23, -0.96)	0.23 (-2.66, 5.85)	
Quadriceps CSA	-2.09 (-8.54, -2.95)		
Hamstrings CSA	-2.01 (-7.95, -2.54)		
Calf CSA	-3.03 (-15.75, -7.82)		
Bench Press Force	-0.08 (-5.55, 4.46)	0.20 (-3.39, 6.01)	0.12 (-5.24, 6.88)
Bench Press Power	-0.15 (-8.19, 4.78)	0.36 (-3.98, 12.03)	0.33 (-5.18, 12.54)
Bench Press work	-0.27 (-5.54, 2.46)	0.16 (-3.11, 4.94)	0.33 (-2.22, 6.02)
Bench Press 1-RM	0.60 (0.32, 6.22)	1.50 (5.50, 10.80)	

### Fitness for Duty Requirements

Primary goals is to protect astronaut health and performance and to safely and efficiently complete mission tasks such as extravehicular activity (EVA) and vehicle egress after landing back on Earth or on a partial gravity surface. Specifically, we define high risk as a 20% or greater reduction in an endpoint because that threshold is associated with significant performance decrements in a ground-based analog study that evaluated simulated EVA and egress task performance.

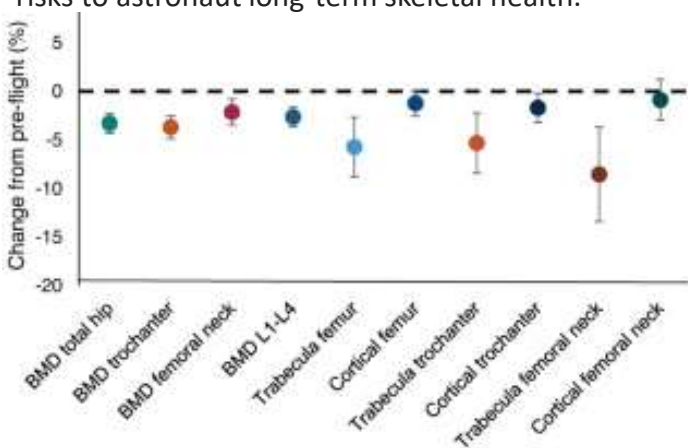
Crewmembers experienced deficits (some with gains) in their lower extremities but did not exceed the requirement and were able to be reconditioned within 30 to 45 days post-mission.



## Background

### Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts – Bone Scott et al., 2019

Bone loss is a known risk of spaceflight with estimates ranging from potential loss of 1-1.5 % loss per month. Determining the extent of bone recovery after prolonged spaceflight is important for understanding risks to astronaut long-term skeletal health.



Many bone endpoints were vulnerable to increasing mission duration. Resistance and treadmill volume loads were the key countermeasure factors associated with improved strength, bone, body composition, and cardiorespiratory endpoints.

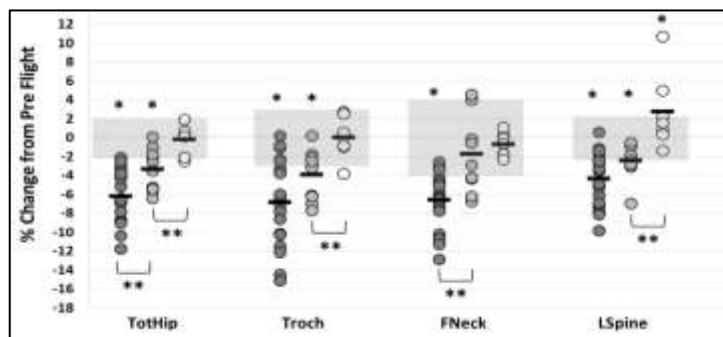
Changes in mean bone mineral density (BMD) were moderate, ranging from  $-2.1\% \pm 0.7\%$  to  $-3.7\% \pm 0.6\%$ ; however much greater declines were observed for bone content in the trabecular regions ( $-5.3\% \pm 1.6\%$  to  $-8.5\% \pm 2.5\%$ )



DXA Total hip	-1.67 (-4.30, -2.28)
DXA Trochanter	-1.55 (-4.88, -2.51)
DXA Femoral neck	-0.84 (-3.47, -0.80)
DXA L1-L4	-1.51 (-3.81, -1.66)
QCT/Trabecular Femoral	-1.52 (-8.79, -2.63)
QCT/Trabecular Trochanter	-1.41 (-8.41, -2.21)
QCT/Trabecular Femoral neck	-1.41 (-13.41, -3.68)
QCT/Cortical Femoral	-0.77 (-2.54, 0.08)
QCT/Cortical Trochanter	-0.88 (-3.21, -0.18)
QCT/Cortical Femoral neck	-0.36 (-2.98, 1.22)

Exercise as a countermeasure to bone loss can also help prevent renal stones which are associated with increased calcium loss from bone.

**Bisphosphonates as a supplement to exercise to protect bone during long duration spaceflight** Study of 7 ISS astronauts (left) who spent mean of 5.5 months on ISS with regular exercise using treadmill, cycle ergometer, and ARED with Bisphosphonate, compared with 18 astronauts using iRED or ARED only. ARED alone provided significant prevention of bone loss compared to iRED, and the combination of ARED and bisphosphonates showed the greatest protection



TotHip = total hip, Troch = trochanter, FNeck = femoral neck, LSpine = lumbar spine

Findings for BMD loss varied between the HDBR studies evaluated. In some, there were no changes in BMD observed which was attributed to the duration of the studies being too short to capture changes to BMD (Ploutz-Snyder et al., 2018; Wang et al., 2023). Other studies observed minor changes in BMD during HDBR studies, with exercise countermeasures providing some level of protection to these changes (Belavy et al., 2011; Zwart et al., 2008).

#### 4.7.2 In-Mission Bone Countermeasures

[V1 4027] Countermeasures **shall** maintain bone mineral density of the hip and spine **at or above 95%** of pre-mission values and **at or above 90%** for the femoral neck. *From NASA-STD-3001 Vol 1, Rev C*



## Application

### Post-flight Training Exercise Prescription (Reconditioning)

Focus on all deficits and return each crewmember back to preflight status as quickly as possible

- Originally, postflight reconditioning was approached very conservatively
- Process has evolved and become much more aggressive which decreased recovery time
- Since the introduction of improved exercise protocols and hardware on ISS, crewmembers are returning in much better physical condition

### Post-flight Reconditioning Timeline

- Re-adaption to gravity begin upon re-entry and landing (R+0)
- Reconditioning program lasts 45 days starting R+1
- Reconditioning is scheduled for 2 hours per day/7 days a week, flexible if needed
- Crewmember, Flight Surgeon and ACSR can request additional time past 45 days if needed

### Reconditioning is a Dynamic Program

- Uses functional movement patterns
- Uses multiple planes at multiple joints
- Emphasis is tailored to individual deficits

### Functional Fitness Assessment

- Data is used to determine conditioning status as compared to preflight levels
- Pre-flight baseline performed at L-60
- Post-flight performed at R+7 and R+30
- Crewmembers are reassessed across the span of their lifetime



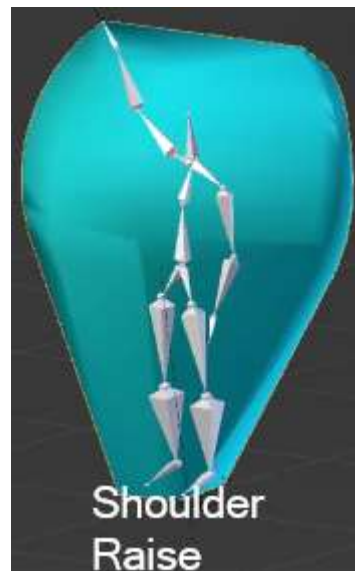
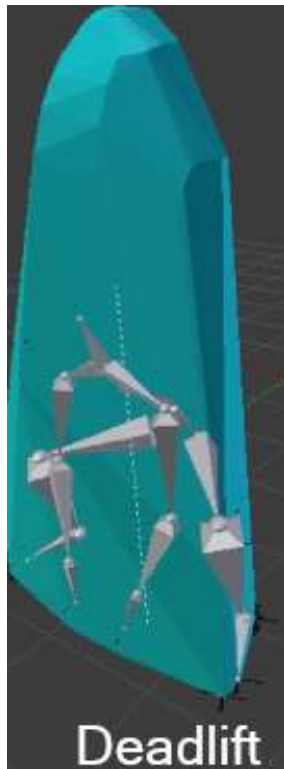
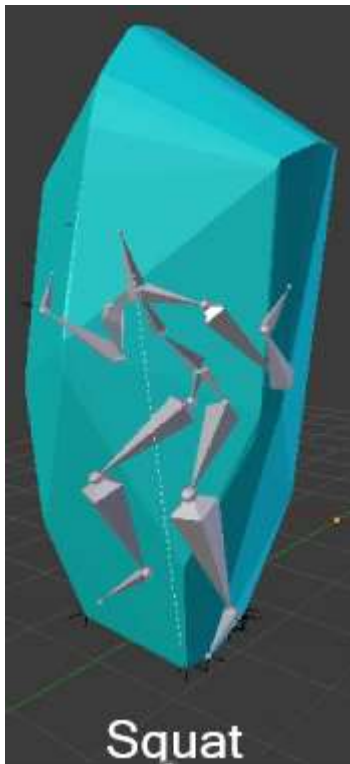




## Design Considerations

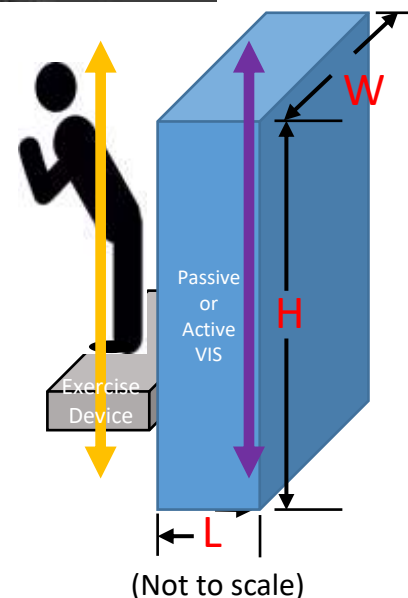
Program managers and vehicle developers must consider the system limitations and capabilities when designing and building exercise equipment and hardware for various spacecrafts. Some of these considerations include:

- The vibration produced when exercise equipment is in use, such as the vibration isolation and stabilization (VIS) system.
- The needed resistive force, mass, and power required for the vehicle to operate the exercise system.
- The required data collection capability to track crewmember performance (i.e., heart rate,  $VO_{2max}$ , etc.).
- The mass and volume requirements for the vehicle to accommodate the exercise system and human movement (see example graphics below).



The vehicle must be designed to accommodate all aspects of the exercise system (i.e., mass, volume, vibration) as well as the volume envelope required for human movement while exercising.

**Vehicle structural fatigue must be considered when designing the vibration isolation and stabilization system (VIS).**





## Summary

### Summary of Exercise Standards and Physiological Outcomes for Different Mission Durations

Flight Data from Greenisen 1999<sup>1</sup> & Scott 2023<sup>2</sup>

#### Aerobic Standard

- Maintain 80% pre-flight  $VO_{2max}$

Exercise Type & Mission Duration	Exercise Session Frequency	Exercise Session Duration	Equipment/Hardware	Hardware Capabilities	Crew Usage	Physiological Decrements
<b>Very Short Duration</b> ( $< 10$ days) <sup>1</sup>	No exercise	No exercise	Shuttle upright ergometer	<b>Speed:</b> 50 to 120 RPM <b>Load:</b> 0 to 350 Watts (25 W increments)	N/A	Average -11% $VO_{2max}$
<b>Short Duration</b> (up to 14 days) <sup>1</sup>	3 days/week	20 minutes/session (variable)	Shuttle upright ergometer	<b>Speed:</b> 50 to 120 RPM <b>Load:</b> 0 to 350 Watts (25 W increments)	1. 3 sessions/week for $\geq 20$ minutes; $\geq 70\%$ peak heart rate 2. 3 sessions/week for $\geq 20$ minutes; $< 70\%$ peak heart rate 3. $< 3$ sessions/week; variable session time and heart rate	1. Average: -9.2% $VO_{2max}$ 2. Average: -15.3% $VO_{2max}$ 3. Average -22.6% $VO_{2max}$
<b>Long Duration</b> (180+ days) <sup>2</sup>	6-7 days/week	30 minutes/session	ISS Second-generation treadmill with vibration isolation and stabilization (T2)  ISS Cycle ergometer with vibration isolation and stabilization (CEVIS)	<b>Speed:</b> up to 12.7 mph <b>Load:</b> up to 70% body mass <b>Peak heart rate:</b> 70-90% max HR  <b>Speed:</b> up to 100 RPM <b>Load:</b> peak 200 Watts <b>Peak heart rate:</b> 70-90% max HR	<b>T2:</b> 47% of days on orbit for 27 minutes; 70% peak heart rate for 69% of sessions (162 peak bpm); 7-8mph; average 68% body mass loading  <b>CEVIS:</b> 37% of days on orbit for 26 minutes; 70% peak heart rate for 76% of sessions (163 peak bpm); 78-92mph; average load of 137 Watts	Average: -7.4% $VO_{2max}$ Range: -2.35 to -11.21 $VO_{2max}$

#### Strength & Bone Standards

- Maintain 80% of pre-flight muscle strength
- Maintain 95% of pre-flight hip and spine and 90% femoral neck bone mineral density

Exercise Type & Mission Duration	Exercise Session Frequency	Exercise Session Duration	Equipment/Hardware	Hardware Capabilities	Crew Usage	Physiological Decrements
<b>Very Short Duration</b> ( $< 10$ days) <sup>1</sup>	No exercise	No exercise	Shuttle Treadmill only, no resistive exercise	<b>Load Capacity:</b> max 220lbs.	N/A	Muscle strength loss: -12% to -19% in upper leg -3% to -10% in lower leg -2% to -23% in back  < 1.5% BMD loss
<b>Short Duration</b> (up to 14 days) <sup>1</sup>	3 days/week	Variable	Shuttle Treadmill only, no resistive exercise	<b>Load Capacity:</b> max 220lbs.	Continuous and interval exercise training at 60-85% of pre-flight $VO_{2max}$	Muscle strength loss: -2% to -9% in upper leg -5% to +12% in lower leg -15% to -38% in back  < 1.5% BMD loss
<b>Long Duration</b> (180+ days) <sup>2</sup>	6-7 days/week	60 minutes/session	ISS Advanced resistive exercise device (ARED)	<b>600lb. load capability</b> <u>Critical Exercises:</u> ▪ Rowing ▪ Squat press ▪ Squat ▪ Deadlift ▪ Shoulder raise ▪ Cable chop (standing) <u>Additional Exercises:</u> • Kneeling chop • Bell swing • Leg abduction • Leg flexion	<b>Bench Press:</b> Average 44 repetitions; load range 98-153lbs. <b>Squat:</b> Average 189 days; load range 150-223lbs. <b>Heel Raise:</b> Average 207 repetitions; load range 198-293lbs. <b>Deadlift:</b> Average 230 repetitions; load range 156-215lbs.	<b>Average:</b> -1% loss of upper body strength; -9% loss of lower body strength <b>Range:</b> -1% to -3% loss of upper body strength; -4 to -12% loss of lower body strength  <b>Average:</b> -0.5 to 1.0% BMD loss per month <b>Range:</b> -2.1% to -8.5% BMD loss

Data from this table can be used to determine exercise hardware, capabilities, and protocols for varying mission duration lengths.



# Back-Up





View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the [OCHMO Standards website](#)

## Referenced Technical Requirements

### NASA-STD-3001 Volume 1, Rev C

**[V1 3017] Post-Mission Reconditioning** Post-mission reconditioning shall be aimed at returning to baseline muscle strength.

**[V1 4001] Microgravity EVA Aerobic Capacity** Crewmembers shall maintain an in-mission  $VO_{2max}$  at or above 32.9 ml/(min/kg) for missions with microgravity EVAs as determined by either direct or indirect measures.

**[V1 4002] Extraterrestrial Surface EVA Aerobic Capacity** Crewmembers shall maintain an in-mission maximum aerobic capacity ( $VO_{2max}$ ) at or above 36.5 ml/(min/kg) for missions with celestial surface EVAs as determined by either direct or indirect measures.

**[V1 4003] In-Mission Aerobic Capacity** The in-mission aerobic capacity shall be maintained, either through countermeasures or work performance, at or above 80% of the pre-mission capacity determined by either direct or indirect measures.

**[V1 4004] Post-Mission Aerobic Capacity** The post-mission reconditioning shall be aimed at achieving a  $VO_{2max}$  at or above the crewmember's pre-mission values.

**[V1 4023] Pre-Mission Muscle Strength and Function** Pre-mission muscle strength and function shall be per the values in Table 2, Pre-Mission Muscle Strength Requirements.

**[V1 4024] In-Mission Skeletal and Muscle Strength** Countermeasures shall maintain in-mission skeletal muscle strength at or above 80% of baseline values.

### NASA-STD-3001 Volume 2, Rev D

**[V2 7038] Physiological Countermeasures Capability** The system shall provide countermeasures to meet crew bone, muscle, sensorimotor, thermoregulation, and aerobic/cardiovascular requirements defined in NASA-STD-3001, Volume 1

**[V2 7040] Physiological Countermeasure Operations** The physiological countermeasure system design shall allow the crew to unstow supplies, perform operations, and stow items within the allotted countermeasure schedule.

**[V2 7043] Medical Capability** A medical system shall be provided to the crew to meet the medical requirements of NASA-STD-3001, Volume 1.

**[V2 8001] Volume Allocation** The system shall provide the defined habitable volume and layout to physically accommodate crew operations and living



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