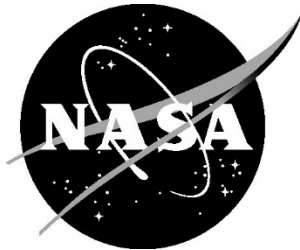


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# Astronaut physiological deconditioning and exercise prescription countermeasures in spaceflight

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# **Astronaut physiological deconditioning and exercise prescription countermeasures in spaceflight**

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## **ABSTRACT**

The human skeletal muscular and cardiovascular systems are adapted to the upright posture of Earth's gravitational environment. Astronauts experience an altered gravity environment in spaceflight that leads to a number of physiological changes and decrements to these systems that can decrease overall crew performance. Countermeasures, including prescribed exercise during spaceflight, is vital for astronauts to maintain optimal health and performance. The degree of physiological deconditioning is dependent on a multitude of factors such as sex, age, mission duration, fitness level, and gravity environments experienced. Deconditioning begins immediately upon entering an altered gravity environment and physiological decrements of the skeletal muscular and cardiovascular systems are measurable among astronauts within a few days. Thus, to maintain their physical fitness, ability to perform mission duties, and be able to egress vehicles when needed, it is imperative that astronauts participate in exercise during all phases of flight. This is especially important for long duration flights where deconditioning effects can be more deleterious. The NASA Office of the Chief Health and Medical Officer 3001 Standards Team develops requirements utilized by commercial and international partners to better understand spaceflight-induced physiological changes and countermeasures and expected outcomes with or without exercise.

## INTRODUCTION

There is a myriad of data on the changes that astronauts face when in microgravity. Research studies and occupational measures have been taken since the first spaceflight of humans. Systematic reviews have been performed (1) that separate the data by categories such as skeletal muscle responses to microgravity ( $\mu\text{G}$ ) in humans, skeletal muscle responses to  $\mu\text{G}$  in animals, adaptation of the skeletal system to  $\mu\text{G}$  in humans, adaptation of the skeletal system to  $\mu\text{G}$  in animals, and effectiveness of exercise countermeasure on musculoskeletal system in spaceflight. All the studies (animal and human) corroborate that microgravity exposure leads to decrements in the muscle skeletal system, even with exercise (1). The goal of this paper is to utilize the data on the effectiveness of countermeasures on human physiology and determine an appropriate metric to measure the effectiveness. The metric must be non-invasive, repeatable, and easily measured. Based on this criterion, NASA focused on human studies that utilized and measured the effect of exercise systems in spaceflight on human physiology with non-invasive measures.

The physiological changes that astronauts face when entering an altered gravity environment, including fluid shifts to the head and torso, bone demineralization, decreases in aerobic capacity, and muscle mass loss (2,3). Sustained exposure to microgravity and body fluid redistribution is associated with cardiovascular changes leading to total blood volume reduction, changes in maximal heart rate, blood pressure, arteriovenous oxygen, decreased cardiac muscle mass, and reduced aerobic capacity (4,5). Past research has found that maximal oxygen uptake is decreased by as much as 22% during a short duration spaceflight mission of 9-14 days (5). Loss of muscle mass, volume, and strength during spaceflight is most influenced by the lack of gravitational loading on the muscles (6). Weightlessness in microgravity and reduced muscle loading leads to a reduction in the size of muscle fibers, decreased protein synthesis in the muscle fibers, and an overall increase in protein degradation (3). Extensor and flexor type muscles may lose up to 30% isokinetic torque during long duration spaceflight missions (6). Similarly, microgravity and weightlessness also leads to reduced loads on astronauts' bones and accelerated bone turnover (7). Bone demineralization and bone loss during spaceflight results in calcium leaving the bones,

with urinary calcium excretion increased by 60-70% within the first few days of exposure to the microgravity environment (2). Past research has suggested that bone mineral density reduction rates during spaceflight are as high as 0.5-1.5% per month (7,8). In sum, there is a great need for evidence-based guidelines and exercise countermeasures for astronauts to lessen the effects of microgravity deconditioning and improve overall astronaut health and mission outcomes.

#### *Historical exercise practices in spaceflight*

During the early days of human spaceflight, exercise and physical activity initially sought to observe the effects of physiological effects of a microgravity environment (9). Project Mercury was the first U.S. spaceflight program that made medical observations on crewmembers, where they performed basic exercise practices by pulling a bungee cord while in orbit (9). Upon their return to Earth, Mercury crewmembers were observed to have some postural hypotension which led to the NASA Aerospace Medical Operations Office in 1962 to make the statement that a “*prescribed inflight exercise program may be necessary to preclude symptoms in case of the need for an emergency egress soon after landing*” (9,10).

The Apollo program is the first spaceflight program to implement exercise countermeasures during spaceflight. Crewmembers utilized the ‘Apollo Exerciser’, which was a modified version of a commercially available variable resistance rope friction device. The Apollo astronauts performed exercises using the device at varying frequency and intensity without a prescribed exercise program (9). Pre-flight and post-flight exercise response testing of astronauts was conducted to observe any changes to cardiopulmonary status resulting from Spaceflight. Findings from the *Biomedical Results of Apollo* released by NASA in 1975 (11) found several significant changes immediately post-flight:

- Significant alterations in the relationship between heart rate and oxygen consumption.
- Significant decrease in systolic and diastolic blood pressure attained at a given heart rate level.
- Statistically significant decrease in cardiac output at a heart rate of 160 beats per minute.

The post-flight decline observed immediately after spaceflight and rapid normalization of the astronauts' response to exercise was thought to be related to a decrease in plasma volume (12).

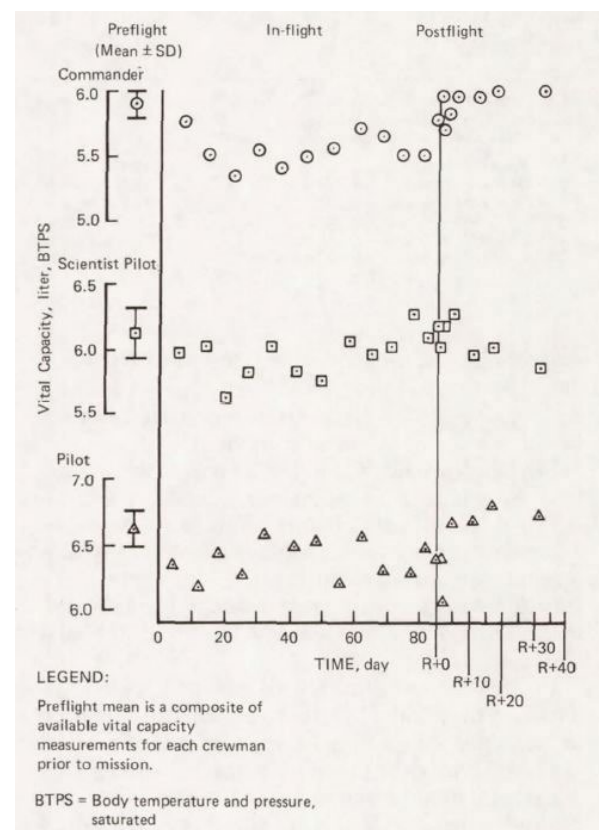
The Skylab program ran from 1973 to 1974 and was the first long-duration spaceflight program at NASA. Skylab-2 introduced a prescribed exercise countermeasure for crewmembers to utilize the M171 cycle ergometer for 30 minutes per day. The following Skylab-3 increased this time to 60 minutes per day, and added a new isokinetic device referred to as the 'Mini-Gym'. Skylab-4 further increased exercise allowance to 90 minutes per day and added a treadmill-like system (9). Results from the observations found that there was some BMD loss among crewmembers post-flight, but were not to levels of clinical concern (13). A reduction in leg extensor strength was observed in some of the Skylab missions with recovery to crew standing and walking without difficulty the day after landing/recovery (9,13). Clinical observations found no marked changes to the  $VO_{2max}$  during flight and even concluded that  $VO_{2max}$  slightly increased during flight in some crewmembers. Heart rate response to exercise was elevated immediately post-flight and returned to pre-flight levels by approximately 24 days post-landing (12,13). See Figure 1.

Skylab 4 Vital Capacity Data for a summary of changes to aerobic capacity during the Skylab 4 mission.

The NASA Shuttle Program gathered historical physiological and exercise data throughout its 135 flights from 1981 to 2008.

The primary exercise device on Shuttle was the cycle ergometer, with additional treadmills and a rower later added for evaluation. Flight rules included exercise countermeasures to be performed no less than every other day for the

Commander, Flight Engineer, and Pilot, and every third day for Payload and Mission Specialists (9). A general summary of the results from numerous medical reports and observations of Shuttle astronauts found (14):



**Figure 1. Skylab 4 Vital Capacity Data**  
Summary of changes to aerobic capacity during the Skylab 4 mission. From: *Biomedical Results from Skylab (1977)*

- Post-landing loss of isometric muscle strength by an average 10% decrease (14).
- Non-exercisers on Shuttle showed a significant 12-15% decrease in  $VO_{2max}$  compared to crewmembers who utilized the treadmill (-3%) and rower (-6%); and crew who exercised >3 days vs. those who exercised <3 days during spaceflight had a lower heart rate response and maintained pulse pressure during post-flight orthostatic testing (9).
- The shorter duration of Shuttle missions were insufficient in detecting changes in bone density among crewmembers, but MRIs conducted pre- and post-flight provided data on regional bone response to post-flight loads (14).

#### *Head-down bed rest studies*

Research utilizing head-down bed rest (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 (15–20). During these studies, participants are placed on strict bed rest at a specified degree of head-down tilt where they must complete all daily activities while in bed for short (5 to 14 days), medium (15 to 59 days) or long (60+ days) duration timelines (21). Researchers have investigated potential countermeasures to address these physiological decrements during HDBR studies, including exercise protocols to mitigate BMD loss and muscle and cardiovascular changes (22–25). These countermeasures were overall effective in maintaining, and in some cases improving, cardiovascular and aerobic health (22,24,25) and mitigating loss of muscular strength (23–25). Findings for BMD loss varies between the HDBR studies evaluated. In some studies, there were no changes in BMD observed which was attributed to the duration of the studies being too short to capture changes to BMD (25,26). Other studies observed minor changes in BMD during HDBR studies, with exercise countermeasures providing some level of protection to these changes (27,28).



### *NASA-STD-3001 technical requirements*

The Office of the Chief Health and Medical Officer at the National Aeronautics and Space Administration (NASA) manages a set of documents called NASA-STD-3001, which are Agency-level spaceflight human system standards that are applicable to all human spaceflight programs (29). NASA-STD-3001 consists of two volumes, Volume 1: Crew Health and Volume 2: Human Factors, Habitability, and Environmental Health. These Agency standards enable human spaceflight missions through minimizing health risks, providing vehicle design parameters, and supporting the performance of the crew. Within each document are technical requirements that include a ‘shall’ statement that is required for consideration when developing program-specific human-rated system design requirements. Each technical requirement also includes a rationale that provides additional background information and evidence for the purpose of the technical requirement, and guidance on potential ways to verify the technical requirement is being met. Read the article entitled *NASA Space Flight Human-System Standard: enabling human spaceflight missions by supporting astronaut health, safety, and performance* for additional information (30).

During our systematic review of the literature, we included studies that contained full datasets of pre/in/and post-flight data, and those that collected data in a controlled environment (i.e., bed rest studies). There are a plethora of other studies that are relevant to the described topic and are important additions to this body of scientific knowledge (1,31,32). However, we did not include all these studies and articles in our body of work as they do not include the appropriate comprehensive and validated data that can be utilized to create NASA’s recommended 3001 technical requirements for the protection of human physiological performance and health.

### *NASA-STD-3001 Volume 1: Crew Health*

As part of NASA-STD-3001 Volume 1: Crew Health, a set of spaceflight health technical requirements for human performance were developed to provide a declaration of acceptable medical risk from deleterious health and performance effects and support health maintenance of astronauts during

spaceflight missions (33). NASA-STD-3001 Volume 1 includes ‘fitness-for-duty’ technical requirements for aerobic capacity. Aerobic capacity is defined as the maximum amount of oxygen that a person’s body is able to utilize at one time and represents an individual’s ability to efficiently use oxygen. A greater level of aerobic capacity means the body is able to perform more intensive physical work while continuing to use oxygen to produce energy. An astronaut’s aerobic capacity influences their ability to perform tasks at a given level of work; setting aerobic fitness-for-duty parameters ensures that astronauts can perform their required functions during all phases of a spaceflight mission. See Table 1 for the relevant NASA-STD-3001 Aerobic Capacity requirements.

**Table 1. NASA-STD-3001 Volume 1 Aerobic Capacity Fitness-for-Duty Technical Requirements**

| <b>Requirement Title</b>                                | <b>Requirement Shall Statement</b>   |
|---|--|
| [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 $VO_{2max}$ at or above 36.5 ml/min/kg for missions with extraterrestrial 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. |

In addition, there are technical requirements related to permissible outcome limits for muscle strength and bone mineral density (BMD) loss. Maintaining adequate strength during spaceflight is essential for astronauts to be able to perform the required tasks and potential emergency egress procedures from a vehicle. Pre- and in-mission muscle strength and function requirements are designed to provide sufficient strength to complete in-flight and post-flight mission tasks while maintaining operational efficiency and preserving muscle strength for off-nominal events. When astronauts experience BMD loss, they are at increased risk for bone fracture. Additional concern surrounds the fact that not all BMD lost during spaceflight is regained, thus increasing an astronaut’s risk for early onset osteoporosis and fracture risk later in life. Pre- and in-mission BMD requirements are established to ensure astronauts begin a spaceflight mission at an appropriate BMD level and mitigate as much loss of BMD as possible throughout the duration of that mission. See Table 2 for the relevant NASA-STD-3001 Muscle Strength

and Bone Mineral Density requirements. See Table 3 for the relevant NASA-STD-3001 Pre-Mission Muscle Strength requirements.

**Table 2. NASA-STD-3001 Volume 1 Muscle Strength and Bone Mineral Density Fitness-for-Duty Technical Requirements**

| <b>Requirement Title</b>  | <b>Requirement Shall Statement</b>   |
|---|--|
| [V1 4023] Pre-Mission Muscle Strength and Function  | Pre-mission muscle strength and function shall be per the values in Table 4.6-1 Pre-Mission Muscle Strength Technical Requirements. <sup>1</sup>   |
| [V1 4024] In-Mission Skeletal Muscle Strength   | Countermeasures shall maintain in-mission skeletal muscle strength at or above 80% of baseline values.   |
| [V1 4026] Pre-Mission Bone Mineral Density  | Crewmembers' pre-mission bone mineral density (BMD) T-scores for total hip and lumbar spine (L1-L4), as measured by mass dual energy X-ray absorptiometry (DXA) shall be consistent with an age, sex, gender, and ethnic-matched population. |
| [V1 4027] In-Mission Bone Countermeasures   | 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.   |
| <sup>1</sup> See Table 3. NASA-STD-3001 Volume 1: Pre-Mission Muscle Strength Technical Requirements Pre-Mission Muscle Strength Technical Requirements |  |

**Table 3. NASA-STD-3001 Volume 1: Pre-Mission Muscle Strength Technical Requirements Pre-Mission Muscle Strength Technical Requirements**

|             | <b>Minimum</b>    | <b>Microgravity EVAs</b> | <b>Extraterrestrial Surface EVAs</b> | <b>Unaided Terrestrial Egress</b> |
|-------------|-------------------|--------------------------|--------------------------------------|-----------------------------------|
| Deadlift    | 1.0 x Body Weight | 1.3 x Body Weight        | 1.6 x Body Weight                    | 1.3 x Body Weight                 |
| Bench Press | 0.7 x Body Weight | 0.8 x Body Weight        | 1.0 x Body Weight                    | 0.7 x Body Weight                 |

The technical requirements presented in Tables 1 and 2 are based on scientific and clinical evidence and research, lessons learned from previous spaceflight missions and analogue environments, current medical practice, risk management data, and expert recommendations. They are to be considered in conjunction with the technical requirements from NASA-STD-3001 Volume 2, discussed later in this article, to support astronaut health and performance.

### *NASA-STD-3001 Volume 2: Human Factors, Habitability, and Environmental Health*

While NASA-STD-3001 Volume 1 focuses on human physiological functioning, NASA-STD-3001 Volume 2: Human Factors, Habitability, and Environmental Health (34) focuses on human-systems integration and defines the requirements for spacecrafts, internal environments, ground processing, facilities, payloads, and hardware and software systems while considering human health, safety, and

capabilities and limitations. NASA-STD-3001 Volume 2 includes technical requirements that necessitate a vehicle/system to provide the capability for crewmembers to engage in physiological countermeasure activities as needed based on individual program and mission design to attain the fitness-for-duty requirements in NASA-STD-3001 Volume 1. See Table 4 for the physiological countermeasures technical requirements from NASA-STD-3001 Volume 2.

**Table 4. NASA-STD-3001 Volume 2 Physiological Countermeasures Technical Requirements**

| Requirement Title                                  | Requirement Shall Statement   |
|--|---|
| [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.         |

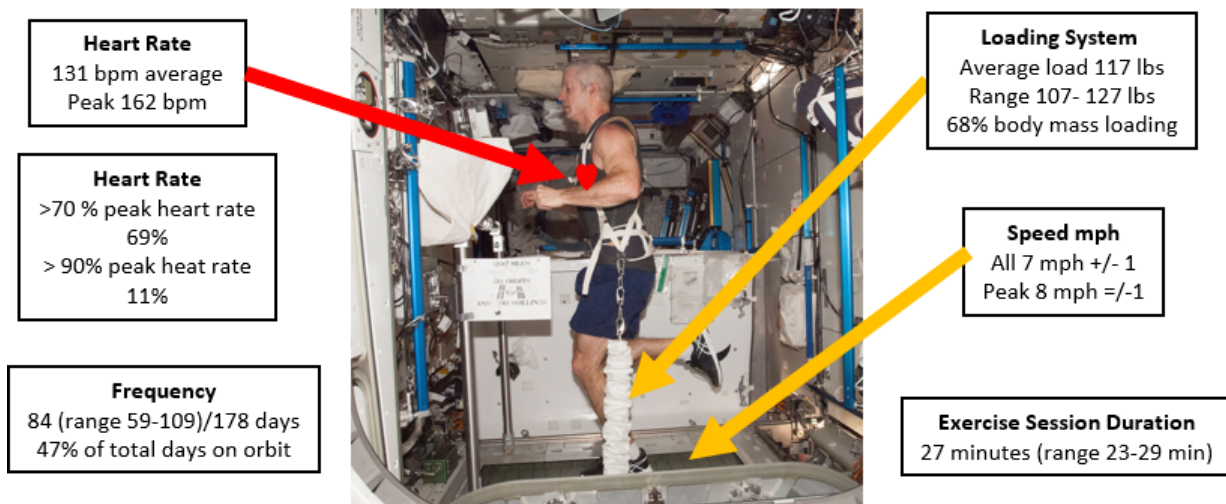
*Current exercise practices in spaceflight*

Based on the historical exercise practices described above, scientific evidence gathered through decades of spaceflight and HDBR studies, and the NASA-STD-3001 fitness-for-duty technical requirements, NASA scientists have developed an exercise prescription for astronauts during their missions to the ISS to mitigate decrements to their cardiovascular system, musculoskeletal system, and bone density. In addition, exercise in-flight improves overall crew health and performance, maximizes reconditioning post-flight, and prevents injury. These exercise practices are monitored and updated as needed, as well as implemented in real-time with currently deployed astronauts, by a group of Astronaut Strength, Conditioning, and Rehabilitation specialists (ASCRs) at NASA (35). The schedule consists of a recommended 2.5 hours a day/6 days a week of exercise with 30-60 minutes of resistive training and average 27 minutes of metabolic/aerobic training, with the remaining time allocated for crew setup and cleanup. Table 5 summarizes these current exercise practices.

**Table 5. Current Spaceflight Exercise Protocol**

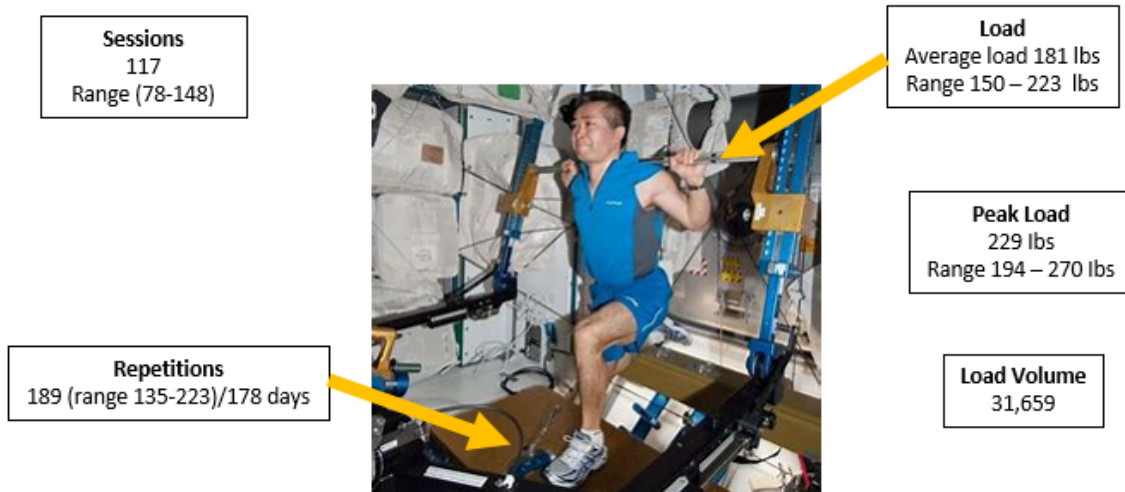
| Type of Exercise  | Protocol Guidelines  | Equipment            |
|-------------------|--|----------------------|
| Metabolic/Aerobic | Average 27 minutes of interval or steady-state training. Based on a pre-flight $VO_{2peak}$ of 70-100%. Increased intensity (watts) based on monthly fitness evaluation and changes in $VO_{2peak}$ .  | CEVIS & T2 Treadmill |
| Resistance        | Average 30-60 minutes of training. Nominally starting crew at their bodyweight or loads from preflight training sessions and increasing based on comfort and capability. Linear progression of loads for upper body; undulating volume for lower body. | ARED                 |

The ISS is equipped with hardware systems designed and engineered to support astronaut exercise countermeasures in microgravity. Over the years, this hardware has advanced and improved significantly. The first two exercise systems flown on the ISS were the treadmill with vibration isolation and stabilization (TVIS) system and the interim resistive exercise device (iRED) (36). From the installment of the TVIS on the ISS in May of 2000, crewmembers reported overall positive feedback on the physical and psychological aspects of utilizing the equipment, but performance issues were reported that led to the development and deployment of the second-generation treadmill referred to as the T2 in November 2009. See Figure 2. ISS Treadmill – T2 for an overview of capabilities.



**Figure 2. ISS Treadmill – T2**  
*Overview of ISS treadmill capabilities*

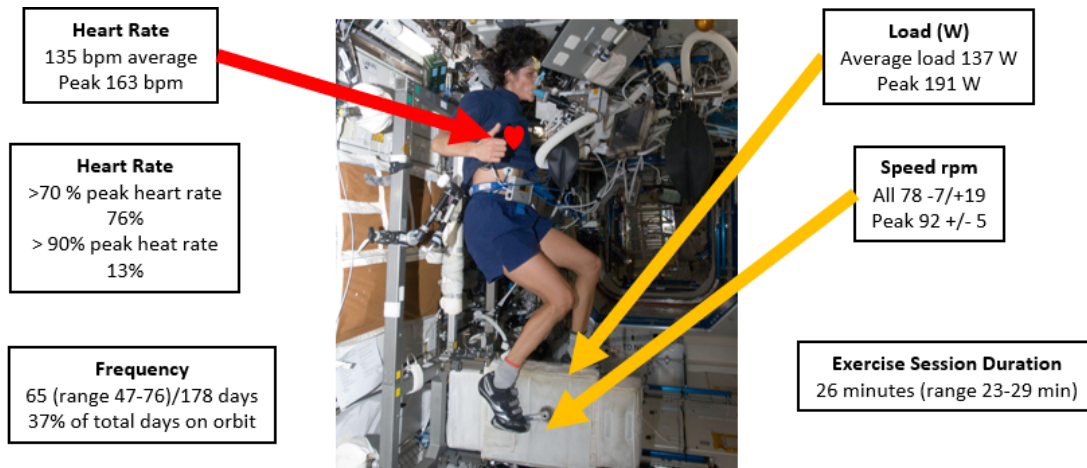
The iRED was initially developed as ‘interim’ hardware to meet initial resistive exercise requirements to counteract muscle and bone loss, and was utilized to gather research data that led to the development of the advanced resistive exercise device (ARED), which was installed on the ISS in 2008 (36). See Figure 3. ISS ARED – Squat for an overview of capabilities.



**Figure 3. ISS ARED – Squat**  
*Overview of ARED capabilities*

In February of 2001, a new aerobic exercise device, the cycle ergometer with vibration isolation and stabilization (CEVIS), was added to expand to the exercise options on the ISS. The CEVIS is considered highly reliable and has been used extensively in-flight without experiencing any in-flight failures (36).

See Figure 4. ISS CEVIS for an overview of capabilities.



**Figure 4. ISS CEVIS**  
*Overview of CEVIS capabilities*

Additional information regarding exercise practices, exercise hardware, and human performance in spaceflight can be found in the NASA OCHMO *Exercise Overview* technical brief (37).

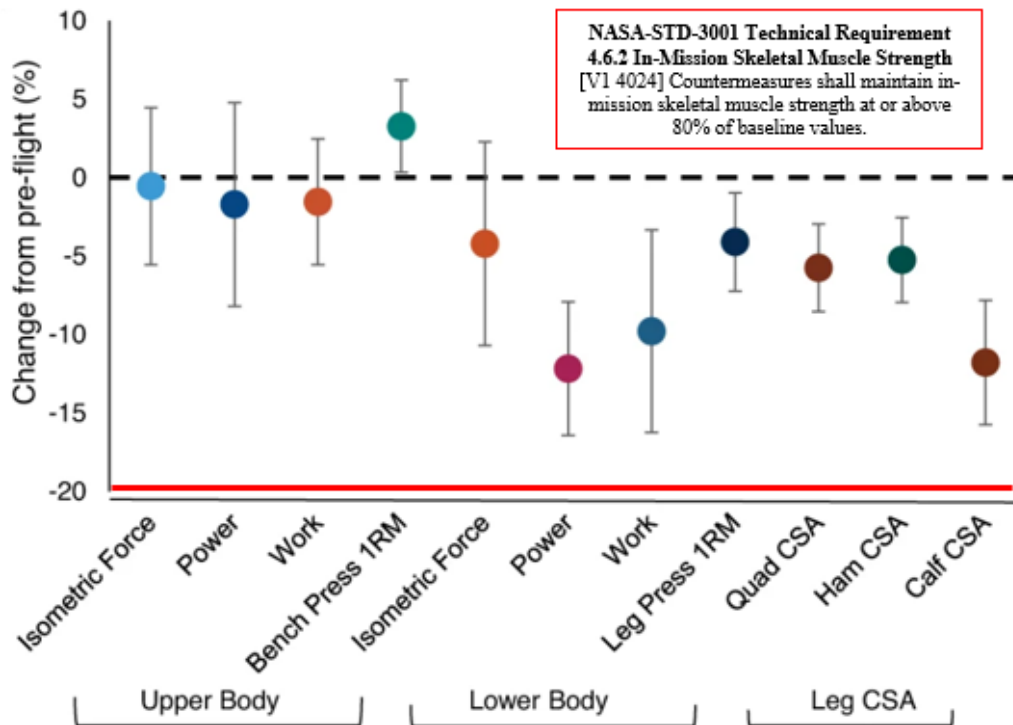
#### *Results from current exercise practices on the ISS*

The use of the current exercise hardware combined with the recommended exercise prescriptions for astronauts on long-duration spaceflight missions to the ISS has been minimally changed in the past 15 years and has enabled researchers to gather data and make assumptions regarding the effectiveness of these practices. One study conducted by NASA is the Integrated Resistance and Aerobic Training Study – SPRINT (38). The objectives of this study were to assess astronaut physical fitness pre-, in-, and post-flight, and evaluate a new aerobic and resistance exercise protocol of higher intensity and lower frequency compared to the previous exercise prescription utilized on the International Space Station (ISS).

A myriad of tests was used to measure astronauts' BMD, muscle strength and function, and cardiorespiratory fitness ( $VO_{2peak}$ ). The study confirmed that routine exercise practices during spaceflight are effective to mitigate muscle strength and function loss, and cardiorespiratory decrements, with greater intensity exercises providing the most protective effects. Declines in isokinetic strength about the knee were significantly lower than crewmembers who utilized the iRED device in earlier missions (39). BMD loss occurred at the expected rate among astronauts participating in exercise countermeasures, with crewmembers utilizing the ARED on average experiencing -2.6% change in the lumbar spine and -4.1% change in the femoral neck, compared to -3.7% lumbar spine and -6.1% femoral neck in crewmembers who participated in resistive exercises using the iRED (39). Cardiorespiratory performance was assessed using  $VO_{2peak}$ , and the current study by English et al. (39) found approximately a 6% decrease in  $VO_{2peak}$  from pre-flight to post-flight, compared to an average 15% decrease of aerobic capacity in earlier spaceflight missions.

A multi-national investigation conducted by NASA of astronauts assigned to ISS missions participated in a study which sought to evaluate the effects of ISS countermeasures on multiple system functions and predicted future performance deconditioning that astronauts may experience on future longer-duration

missions (40). Of the studies summarized in this paper, Scott et al., 2023 (40) provides significant and reliable data results to the larger data pool of astronauts utilized across a vast timeframe. The results of the study found a significant decrease in average lower leg muscle strength, with no changes in mean upper body strength. Cardiorespiratory fitness ( $VO_{2peak}$ ) declined by  $7.4\% \pm 2.0\%$  from pre-flight to post-flight; and mean BMD changes were moderate and ranged from  $-2.1\% \pm 0.7\%$  to  $-3.7\% \pm 0.6\%$  (40). The results from Scott et al. (2023) can be compared to the NASA-STD-3001 technical requirements for exercise countermeasures described previously. For resistive exercise and muscular strength, NASA-STD-3001 Volume 1, Rev B requires that crewmembers maintain skeletal muscle strength at or above 80% of baseline values. Although the crewmembers from the study experienced some deficits in muscle strength, they remained within the required limit of overall muscular strength loss. See Figure 5. Estimates of mean percent change in muscle strength and size.

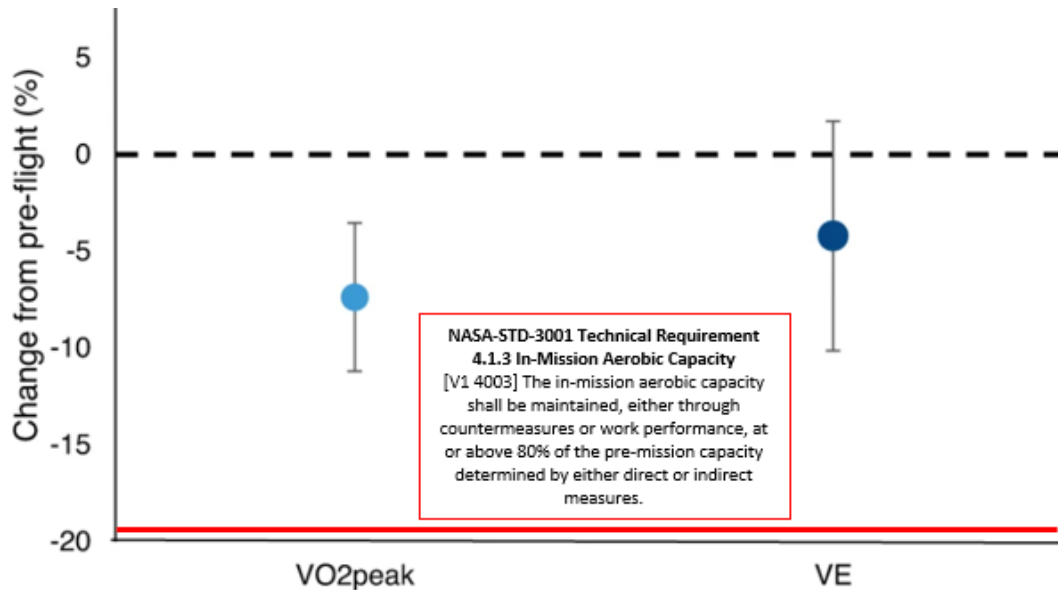


**Figure 5. Estimates of mean percent change in muscle strength and size**  
*Adapted from: Scott et al. (2023) Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts*



For cardiorespiratory fitness, NASA-STD-3001 Volume 1, Rev B requires crewmembers to maintain their aerobic capacity at or above 80% of their pre-mission values. Similar to muscle strength, crewmembers from the study maintained their  $VO_{2peak}$  well above the 20% cut-off. See Figure 6.

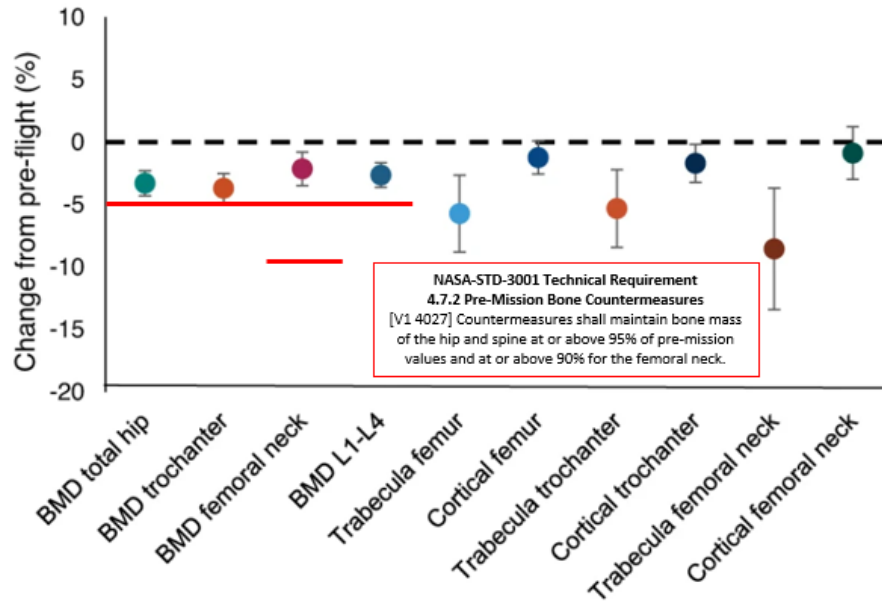
Estimates of mean percent change in aerobic capacity.



**Figure 6. Estimates of mean percent change in aerobic capacity**

*Adapted from: Scott et al. (2023) Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts*

Finally, NASA-STD-3001 Volume 1, Rev B limits BMD loss to at or above 95% of pre-mission values and at or above 90% for the femoral neck. Crewmembers from the Scott et al. (2023) study averaged less than the 5% cut-off for BMD loss and experienced on average a -3% decrease in the femoral neck bone density. See Figure 7. Estimates of mean percent change in bone mineral density.



**Figure 7. Estimates of mean percent change in bone mineral density**

*Adapted from: Scott et al. (2023) Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts*

Overall, the results presented from both the NASA Sprint study and the study conducted by Scott et al. suggests that current exercise hardware and practices are sufficient in maintaining crewmember muscular strength, bone mineral density, and cardiorespiratory fitness as required by NASA-STD-3001 for spaceflight missions to the ISS.

## DISCUSSION

Historical spaceflight experiences thus far have allowed us to gather data and analyze the effectiveness of exercise countermeasures in short-duration, medium-duration, and long-duration missions, with spaceflight missions to the ISS averaging 180 days of flight. See Table 6. Summary of Spaceflight Exercise Countermeasures, Duration of Flight, and Physiological Outcomes.

For the current environment, the NASA-STD-3001 technical requirements are sufficient to protect the crew from the predetermined levels of deficits allowed for muscular strength, BMD loss, and cardiorespiratory health. See Table 7. Summary of Exercise Standards and Physiological Outcomes for Different Mission Durations, for an overview of exercise practices, hardware capabilities, and physiological changes by mission duration.

NASA continues to gain momentum in efforts towards deep space exploration, with the Artemis program returning humans to the Moon and eventually to Mars. These missions will be longer duration than any NASA has experienced before, with the average mission to the lunar surface lasting up to a full year and Mars upwards of 1,200+ days. The functional requirements for human performance during each specific phase of these missions have not been sufficiently defined to determine whether current countermeasures will be adequate to meet the physical performance requirements.

In addition to the increased duration of future missions, there are other considerations that will need to be accounted for when designing requirements and countermeasures to support crew health and performance. Artemis lunar missions will require astronauts to inhabit multiple vehicle systems, including the Orion capsule which will take astronauts from the Earth to the lunar-orbiting Gateway vehicle. The Human Lander System (HLS) will then transport astronauts from Gateway to the lunar surface, where they will traverse the surface of the Moon and transfer between the HLS, lunar habitats, and extraterrestrial vehicles (41). The exercise requirements and capabilities for each of these vehicles will need to be considered synchronously to meet the needs of the crewmembers to prevent physiological decrements. Additionally, with the longer distance and time traveled for these missions, the limitations to vehicles and system capabilities such as mass and storage availability will play a large role in the types of exercise countermeasures that can be accommodated for the crew. The increased distance will also create communication delays with the ground support team, making it difficult to monitor the crewmembers' activity and provide feedback and recommendations. Limited resupply to crew will create obstacles in the event of exercise hardware malfunction and the crew's capability to receive replacement parts to make repairs. Additional information on mission duration considerations for future spaceflight can be found on the NASA OCHMO Mission Duration technical brief (42).

Future considerations for spaceflight exercise, physiological countermeasures, and NASA Standards need to determine if the current Standards need updating to be more stringent in requirements for acceptable decrements to muscle strength, BMD loss, and cardiorespiratory fitness for our crew enduring these longer-duration spaceflight missions. Mission operations will involve more high-tempo and stringent

activity including frequent surface extravehicular activities (EVAs), which will influence the physical needs of the astronauts to perform mission goals.

Long duration spaceflight missions will benefit from novel exercise systems and countermeasures.

Researchers have been working to develop new ways for astronauts to perform exercise and protect their physiological health, including the use of virtual reality games to boost motivation (43), advanced exercise devices (44), and artificial gravity (45). These new exercise approaches in combination with thoroughly researched and crafted Standards will enable future spaceflight to optimize human health and performance and support the overall successful accomplishment of long-duration spaceflight missions.

**Table 6. Summary of Spaceflight Exercise Countermeasures, Duration of Flight, and Physiological Outcomes**

| <b>Spaceflight Program</b>        | <b>Duration</b>  | <b>Exercise Practices</b>   | <b>Outcomes</b>   |
|-----------------------------------|------------------|---|---|
| <b>Apollo (1961-1972)</b>         | 6-12 days        | Apollo Exerciser resistance rope friction device; varying frequency and intensity   | -Decrements to cardiovascular health  |
| <b>Skylab (1973-1974)</b>         | 28-84 days       | M171 cycle ergometer<br>Isokinetic 'Mini-Gym'<br>Treadmill system   | -Non-significant BMD loss<br>-Minor reduction in musculoskeletal strength<br>-No changes to VO <sub>2</sub> max   |
| <b>Shuttle (1981-2008)</b>        | 2-16 days        | Cycle ergometer<br>Treadmills<br>Rower<br>Exercise countermeasures performed every other day or every third day depending on crewmember | -Loss of isometric muscle strength<br>-VO <sub>2</sub> max decreased approx. 67% more among non-exercisers vs. exercisers<br>-Minimal changes to BMD  |
| <b>ISS</b>                        | Average 182 days | 6 days a week of exercise; 27 minutes aerobic and 30-60 minutes resistive training<br>CEVIS, T2 Treadmill, ARED                         | -Decreases in lower body strength<br>-VO <sub>2</sub> peak decline<br>-Moderate BMD loss  |
| <b>Head-Down Bed Rest Studies</b> |                  |   |   |
|                                   | 14 days          | iRAT exercise   | -Effectively prevented cardiovascular and musculoskeletal deconditioning  |
|                                   | 30 days          | Supine treadmill exercise   | -Decline in cardiovascular markers and VO <sub>2</sub> peak in non-exercise controls<br>-Mitigation of BMD loss in exercisers<br>-Maintenance of muscle strength and endurance in exercisers  |
|                                   | 60-70 days       | Resistive vibration or resistive only exercise<br>Flywheel and supine treadmill   | -Minor differences in BMD among exercisers vs. non-exercisers<br>-Preserved muscle metabolic profiles in exercisers<br>-Maintenance of pre-bedrest VO <sub>2</sub> peak in exercisers         |
|                                   | 90 days          | Flywheel resistive exercise<br>Elastic resistance bands<br>Cycle ergometer exercises<br>Vertical treadmill                              | -Prevention of VO <sub>2</sub> max decline<br>-Mitigation of muscle strength loss<br>-No significant changes in BMD; some observed changes in urine amino-terminal peptides in non-exercisers |

**Table 7. Summary of Exercise Standards and Physiological Outcomes for Different Mission Durations**

| <b>Aerobic Standard</b> <ul style="list-style-type: none"> <li>Maintain 80% pre-flight <math>VO_{2max}</math></li> </ul>  |                            |                               |   |  |   |  |
|---|----------------------------|-------------------------------|---|--|---|--|
| Exercise Type & Mission Duration  | Exercise Session Frequency | Exercise Session Duration     | Equipment/Hardware  | Hardware Capabilities  | Crew Usage  | Physiological Decrements   |
| <b>Very Short Duration (&lt; 10 days)<sup>1</sup></b>   | No exercise                | No exercise                   | Shuttle upright ergometer   | <b>Speed:</b> 50 to 120 RPM<br><b>Load:</b> 0 to 350 Watts (25 W increments)   | N/A   | Average -11% $VO_{2max}$   |
| <b>Short Duration (up to 14 days)<sup>1</sup></b>   | 3 days/week                | 20 minutes/session (variable) | Shuttle upright ergometer   | <b>Speed:</b> 50 to 120 RPM<br><b>Load:</b> 0 to 350 Watts (25 W increments)   | 1. 3 sessions/week for $\geq 20$ minutes; $\geq 70\%$ peak heart rate<br>2. 3 sessions/week for $\geq 20$ minutes; $< 70\%$ peak heart rate<br>3. $< 3$ sessions/week; variable session time and heart rate   | 1. Average: -9.2% $VO_{2max}$<br>2. Average: -15.3% $VO_{2max}$<br>3. Average -22.6% $VO_{2max}$ |
| <b>Long Duration (180+ days)<sup>2</sup></b>  | 6-7 days/week              | 30 minutes/session            | ISS Second-generation treadmill with vibration isolation and stabilization (T2)<br><br>ISS Cycle ergometer with vibration isolation and stabilization (CEVIS) | <b>Speed:</b> up to 12.7 mph<br><b>Load:</b> up to 70% body mass<br><b>Peak heart rate:</b> 70-90% max HR<br><br><b>Speed:</b> up to 100 RPM<br><b>Load:</b> peak 200 Watts<br><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<br><br><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% $VO_{2max}$<br>Range: -2.35 to -11.21 $VO_{2max}$                                 |
| <b>Strength &amp; Bone Standards</b> <ul style="list-style-type: none"> <li>Maintain 80% of pre-flight muscle strength</li> <li>Maintain 95% of pre-flight hip and spine and 90% femoral neck bone mineral density</li> </ul> |                            |                               |   |  |   |  |
| <b>Short Duration</b>   | 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  |

|   |               |                    |   |  |  |   |
|---|---------------|--------------------|---|--|--|---|
| <b>(up to 14 days)<sup>1</sup></b>                |               |                    |   |  |  | <p>-3% to -10% in lower leg<br/>-2% to -23% in back</p> <p>&lt; 1.5% BMD loss</p>   |
| <b>Short Duration (up to 14 days)<sup>1</sup></b> | 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 <sub>2max</sub>   | <p>Muscle strength loss:<br/>-2% to -9% in upper leg<br/>-5% to +12% in lower leg<br/>-15% to -38% in back</p> <p>&lt; 1.5% BMD loss</p>  |
| <b>Long Duration (180+ days)<sup>2</sup></b>      | 6-7 days/week | 60 minutes/session | ISS Advanced resistive exercise device (ARED) | <p><b>600lb. load capability</b></p> <p><u>Critical Exercises:</u></p> <ul style="list-style-type: none"> <li>▪ Rowing</li> <li>▪ Squat press</li> <li>▪ Squat</li> <li>▪ Deadlift</li> <li>▪ Shoulder raise</li> <li>▪ Cable chop (standing)</li> </ul> <p><u>Additional Exercises:</u></p> <ul style="list-style-type: none"> <li>• Kneeling chop</li> <li>• Bell swing</li> <li>• Leg abduction</li> <li>• Leg flexion</li> </ul> | <p><b>Bench Press:</b> Average 44 repetitions; load range 98-153lbs.</p> <p><b>Squat:</b> Average 189 days; load range 150-223lbs.</p> <p><b>Heel Raise:</b> Average 207 repetitions; load range 198-293lbs.</p> <p><b>Deadlift:</b> Average 230 repetitions; load range 156-215lbs.</p> | <p><b>Average:</b> -1% loss of upper body strength; -9% loss of lower body strength</p> <p><b>Range:</b> -1% to -3% loss of upper body strength; -4 to -12% loss of lower body strength</p> <p><b>Average:</b> -0.5 to 1.0% BMD loss per month</p> <p><b>Range:</b> -2.1% to -8.5% BMD loss</p> |

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