BRIEF REVIEW

The Astronaut-Athlete: Optimizing Human Performance in Space

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[1]*Department of Health, Nutrition, and Exercise Science, North Dakota State University, Fargo, North Dakota;* [2]*Exercise Physiology and Countermeasures Laboratory, Universities Space Research Association, Houston, Texas;* [3]*National Aeronautics and Space Administration, Exercise Physiology and Countermeasures Laboratory, Houston, Texas;* [4]*Exercise Physiology and Countermeasures Laboratory, JES Tech, Houston, Texas; and* [5]*Department of Health and Human Performance, University of Houston, Houston, Texas*

Abstract

Hackney, KJ, Scott, JM, Hanson, AM, English, KL, Downs, ME, and Ploutz-Snyder, LL. The astronaut-athlete: optimizing human performance in space. *J Strength Cond Res* 29(12): 3531–3545, 2015—It is well known that long-duration spaceflight results in deconditioning of neuromuscular and cardiovascular systems, leading to a decline in physical fitness. On reloading in gravitational environments, reduced fitness (e.g., aerobic capacity, muscular strength, and endurance) could impair human performance, mission success, and crew safety. The level of fitness necessary for the performance of routine and off-nominal terrestrial mission tasks remains an unanswered and pressing question for scientists and flight physicians. To mitigate fitness loss during spaceflight, resistance and aerobic exercise are the most effective countermeasure available to astronauts. Currently, 2.5 $h \cdot d^{-1}$, 6–7 $d \cdot wk^{-1}$ is allotted in crew schedules for exercise to be performed on highly specialized hardware on the International Space Station (ISS). Exercise hardware provides up to 273 kg of loading capability for resistance exercise, treadmill speeds between 0.44 and 5.5 $m \cdot s^{-1}$, and cycle workloads from 0 and 350 W. Compared to ISS missions, future missions beyond low earth orbit will likely be accomplished with less vehicle volume and power allocated for exercise hardware. Concomitant factors, such as diet and age, will also affect the physiologic responses to exercise training (e.g., anabolic resistance) in the space environment. Research into the potential optimization of exercise countermeasures through use of dietary supplementation, and pharmaceuticals may assist in reducing physiological deconditioning during long-duration spaceflight and have the potential to enhance performance of occupationally related astronaut tasks (e.g., extravehicular activity, habitat construction, equipment repairs, planetary exploration, and emergency response).

Key Words spaceflight, exercise countermeasures, dietary supplementation, pharmaceuticals, aging

Introduction

Over the last 10 years, the strength and conditioning community has expanded its reach beyond its traditional domain of sport athletes into the world of occupational physiologic training. This relatively new field of tactical strength and conditioning is based on the understanding that individuals in physically demanding professions, such as fire and rescue, law enforcement, and military operations, need specialized strength and conditioning programs to ensure optimal occupational performance; as such, these occupational athletes are not dissimilar to traditional sport athletes and require their own needs analyzes to identify the unique demands of their profession (47). Astronauts comprise a very small and unique group within this occupational athlete population, possessing highly diverse athletic and physiologic training backgrounds. These select pilots, engineers, teachers, physicians, scientists, and armed forces members must train and perform in one of the most unique arenas known to humankind. Their job requires them to live and work in an extreme environment that includes microgravity, radiation exposure, social isolation, confinement, reduced daily physical activity, and closed air and water systems. Under these circumstances, astronauts must perform not to secure first place but to complete their mission and return to earth safely. Furthermore, unlike sport athletes who train in focused environments, astronauts have the added challenge of incorporating exercise into an intrinsically catabolic environment (i.e., limited dietary options and reduced mechanical loading) using a small suite of monitoring systems and exercise hardware. Currently, their home, office, and training center are the International Space Station (ISS). The ISS is 109-m wide, has a mass of approximately 420,336 kg, and orbits the earth at 7,700 $m \cdot s^{-1}$ and

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an altitude of 375 km (94). However, it is expected that future missions will take astronauts well beyond low earth orbit and eventually to the surface of other terrestrial bodies such as Mars whose partial gravity environments will substantially increase physiologic demands beyond those of the microgravity that current ISS crewmembers experience. During the extended transits necessary to reach these deep space destinations, reductions in fitness could prevent astronauts from performing critical mission tasks such as a successful unassisted exit from a landing vehicle in the event of an off-nominal (on Mars) or remote landing (on Earth). Furthermore, during these missions, it is expected that the size and available power for exercise equipment will be limited and that crewmembers will be required to maintain their fitness more autonomously because of communication delays with ground personnel. In this review, we first summarize the neuromuscular and cardiovascular fitness adaptations that have been observed in spaceflight and disuse analogs. Second, we explore methods for identifying the fitness levels necessary for adequate performance and mission success. Finally, we review in-flight exercise hardware, exercise prescriptions, and potential methods to optimize in-flight exercise countermeasures for this unique population of astronaut-athletes.

Fitness Loss During Spaceflight and Disuse Analogs

The loss of skeletal mass, strength, and aerobic capacity in response to microgravity exposure has been a medical and physiological concern since the early days of human spaceflight (27,56). The U.S. Space Shuttle program provided an early opportunity to assess several of these outcomes. LeBlanc et al. (78) used magnetic resonance imaging (MRI) to evaluate lower limb muscle volumes before and after an 8-day exposure to microgravity. They observed 6% volume losses for the calf and quadriceps muscle groups. Not surprisingly, more dramatic losses of up to 24% have been documented in these muscle groups after 6 months of spaceflight on the ISS (51,77,78,146). Furthermore, ground-based bed rest analog research has established that quadriceps and calf muscle mass can decrease by 18–30% after 90–120 days of unloading (4,121).

Greater losses in muscle strength relative to muscle mass have generally been observed after long-duration spaceflight; this finding provides some evidence that negative adaptations occur in the nervous system (24,38). For instance, on Mir flights of 6 months duration, 3 cosmonauts showed declines of 20–48% in calf plantar flexion maximal voluntary contraction (MVC) (27). Similar to spaceflight, evidence of strength loss during several different microgravity analogs has been reported, including decrements in MVC of knee extensors up to 16% after 20 days of bed rest (3) to 45% after 90 days of bed rest (3). Large decreases in strength after unilateral lower limb suspension (ULLS), another musculoskeletal unloading analog (55), are also evident, with up to a 42% decline in knee extensor MVC occurring after 21 days (37). There are also significant declines in plantar flexor strength ranging from 15% after 28 days of ULLS (25) to 55% after 90 days of bed rest (113). Although strength decline is generally greater than muscle mass loss, the neural mechanism of adaptation has been elusive. Evidence for a decline in neural drive, obtained using surface electromyography (69), has been reported after 90–180 days of spaceflight. Furthermore, evidence obtained from ground-based analogs using the twitch interpolation technique (24,122) suggests a potential decline in muscle activation; however, prespaceflight and postspaceflight data have not been published (133). Sensorimotor disruptions and postural instability are also well-documented and unwanted adaptations to the space environment (75,76).

Skeletal muscle and the nervous system are clearly not the only systems negatively influenced by unloading as exposure to both spaceflight and bed rest also result in fluid loss, fluid shifts, and cardiac remodeling (12,16). For example, Perhonen et al. (101) demonstrated that left ventricular mass measured by MRI decreased by 8% during 6 weeks of supine bed rest and by 10% after 10 days of spaceflight (101). Although cardiac atrophy does not seem to affect systolic function, cardiac atrophy after spaceflight may impact diastolic function, as shown during 30 days of bed rest (80). Invasive studies of cardiac performance before and after 2 weeks of head-down-tilt bed rest have shown a leftward shift in the diastolic pressure-volume curve after bed rest, resulting in a smaller left ventricular end-diastolic volume for any given filling pressure (84). These reductions result in a decline in upright stroke volume and cardiac output (36,102,132), which may negatively impact aerobic capacity ($\dot{V}O_2$peak). Decreased aerobic capacity during the first 2 weeks of unloading may also be attributed to decreased circulating blood volume (13), although with longer periods of disuse, additional structural changes in the myocardium (101) and the vasculature (153) contribute to impaired performance capacity. Previous work by Levine et al. showed a 20–25% reduction in $\dot{V}O_2$peak associated with 9–14 days of spaceflight (83). In a direct comparison between responses after spaceflight and after bed rest, Trappe et al. (147) reported that the decrease in $\dot{V}O_2$peak during supine cycle ergometry in 4 crewmembers after a 17-day mission (−10%) was comparable with that observed in 8 subjects after 6° head-down-tilt bed rest of the same duration (−7%). Most recently, a 17% decrease in $\dot{V}O_2$peak was measured on the ISS in 14 astronauts after the first 2 weeks of spaceflight. In these astronauts, $\dot{V}O_2$peak increased throughout the remainder of the mission (5–6 months) but never returned to preflight levels (90). It is noted that in the current microgravity environment of the ISS, astronauts are rarely required to perform tasks at maximal intensities, and most activity can be performed with submaximal efforts. However, a reduction in maximal aerobic capacity can result in work being performed at a higher relative percentage of heart rate and $\dot{V}O_2$peak (1). This may be problematic considering that there is a concurrent shift

from slow to fast in skeletal muscle myosin heavy chain isoforms (18,44), which drives energy metabolism toward a greater reliance on carbohydrate to fuel mechanical work (53,141). Therefore, maintaining a high level of aerobic capacity to perform prolonged activity near ventilatory threshold (28) or critical speed (1) is important and a difficult cardiorespiratory fitness parameter to protect during long-duration spaceflight (42,143). For further discussion of spaceflight deconditioning or disuse physiology adaptations, the reader is directed to the following reviews (2,45,46,54,79,93,99,106,135,136).

What Level of Fitness Is Required During Space Missions?

Although the medical health of potential astronauts is rigorously examined during the selection process, the advertised basic qualification requirements do not contain specific stipulations pertaining to fitness (108). As such, astronaut candidates possess a wide variety of athletic backgrounds and training histories ranging from former college football players and marathoners to largely sedentary individuals who perform little or no formal exercise. On flight assignment, astronauts are paired with an Astronaut Strength, Conditioning, and Rehabilitation specialist (ASCR) and work closely with them to increase or maintain preflight fitness, maintain fitness during flight, and recondition after return.

Historically, the purpose of exercise before, during, and after spaceflight has been centered on the protection of the health (both acute and chronic) of the individual astronaut. Without neglecting this health emphasis, the focus has more recently shifted to performance and the importance of identifying occupational physiologic requirements and then training crewmembers to these standards. Currently, there are no established preflight or in-flight fitness requirements (108). Despite this, a basic needs' analysis for astronauts suggests that, particularly in partial and full gravitational environments (e.g., Mars and the Earth), they must possess strength in the postural muscles of the trunk and legs, and also strength and endurance in their shoulders and forearms to work against the external resistance of a pressurized spacesuit and gloves. Metabolically, many astronaut tasks are predominantly aerobic in nature although others, such as setting and operating heavy equipment (e.g., drills on Mars) and performing emergency operations such as egress from a vehicle in the water or rescue of an incapacitated crewmember will necessitate substantial contributions from anaerobic energy systems.

Although fitness standards remain unidentified, minimum thresholds do exist below which crew safety or mission success could be compromised. Identifying such thresholds is difficult as they are highly task specific and thus must be based on the most demanding mission scenarios. Furthermore, the tasks or mission scenarios to be performed by astronauts are not always well-characterized and will vary according to mission destination (Table 1) (108). One logical approach to maintaining higher in-flight fitness levels is to emphasize preflight exercise training to create a higher baseline, further from this threshold of impaired performance (Figure 1). This concept is supported by Moore et al. (90), who showed that astronauts with a higher preflight $\dot{V}O_2$peak generally had greater losses early in flight, but were still at higher levels of aerobic capacity than crewmembers that started with a lower $\dot{V}O_2$peak. Maintaining a high level of aerobic capacity is considered important for numerous operational tasks (e.g., extravehicular activity) and emergency response situations. Recently, Ade et al. showed that running and arm cranking $\dot{V}O_2$peak were significant predictors of 10-km walk-back time, a field test that reflects future terrestrial mission scenarios in which an astronaut would have to walk back to a base area on mechanical failure of a rover (1). For current microgravity missions, National Aeronautics and Space Administration (NASA) attempts to prevent $\dot{V}O_2$peak losses of greater than 25% and to maintain an aerobic capacity greater than 32.9 $ml \cdot kg^{-1} \cdot min^{-1}$ (108), a value based on the metabolic cost of a microgravity spacewalk and that will almost certainly be revised upward for missions to terrestrial surfaces with partial gravity.

As previously discussed, maintaining muscular strength is also an important element for the performance of mission tasks. Identifying strength thresholds is challenging because of the difficulty of earth-based task simulation. Ryder et al. recently used a weighted garment to alter test subjects' strength-to-body weight ratio (0–120% of body weight added) and subsequently evaluated the effect of reduced relative strength on the performance of astronaut-related occupational tasks (supine and upright seat egress and walk, rise from fall, hatch opening, ladder climb, object carry, and construction activity) (117). This novel approach is one of the few available methods to identify strength thresholds for spaceflight mission tasks. In this study, isometric leg-press strength relative to body weight ratios below 17.9 $Nm \cdot kg^{-1}$ showed compromised performance (time to task completion) during upright seated egress and walk (117). This weighted-garment model was strengthened when preflight and postflight astronaut data were included, and it demonstrates a threshold of strength that is required for optimal performance of a simple laboratory-based egress task. It is important to note that the tasks required only 15–30 seconds to perform and were not physically demanding; although this precludes implementing the threshold for operational use, it demonstrates a viable strategy for establishing mission-related strength thresholds. For comparison, previous work with healthy older adults (no weighted garment) shows that isometric unilateral knee-extension strength of 3.0 $Nm \cdot kg^{-1}$ is the threshold below which performance of everyday activities declines, at least for men and women in their eighth decade of life (109). In the absence of established thresholds for the performance of mission tasks, NASA's current goal is to limit strength losses to no greater than

TABLE 1. Examples of potential occupational tasks based on mission destination.*

Mission destination	Energetics required
ISS (0 g)	
Emergency egress on return to earth on land or water	Power, strength, and muscular endurance (water)
EVA	Muscular and cardiovascular endurance
Remote arm operation	Fine motor skill and steadiness
Moon (1/6 g)	
Emergency egress on return to earth on land or water	Power, strength, and muscular endurance (water)
10-km walk	Cardiovascular endurance and strength
Hatch opening	Strength and power
Construction task	Strength and cardiovascular endurance
Ladder climb	Muscular endurance and strength
Sample retrieval	Strength, steadiness, and balance
Other types of EVA	Strength and cardiovascular endurance
Asteroid (unknown g)	
Emergency egress on return to earth on land or water	Power, strength, and endurance (water)
Sample retrieval	Muscular endurance, steadiness, and balance
Other types of EVA	Strength and cardiovascular endurance
Mars (1/3 g)	
Emergency egress on return to earth on land or water	Power, strength, and endurance (water)
Hatch opening	Strength and power
Construction task	Strength and cardiovascular endurance
Ladder climb	Muscular endurance and strength
Sample retrieval	Strength, steadiness, and balance
Other types of EVA	Strength and cardiovascular endurance

*EVA = extravehicular activity.

20% during spaceflight (108). Research planned over the next several years will further elucidate muscle strength and power thresholds below which performance of mission-related tasks may be compromised.

Resistance and Cardiovascular Exercise Countermeasures in Space

Exercise is the cornerstone of countermeasures to prevent unloading-induced remodeling of physiological systems (29). The design of exercise hardware has evolved with our understanding of what is required to keep astronauts healthy during extended-duration missions (7,56). A summary of exercise capabilities by era is shown in Table 2 (7). The current suite of ISS exercise hardware is more robust than ever, and U.S.-provided hardware includes the advanced resistive exercise device (ARED, Figure 2), the cycle ergometer with vibration isolation system (CEVIS, Figure 3), and the second-generation treadmill (T2, Figure 4). Each exercise device is mounted on a vibration isolation system to protect the structural integrity of the ISS by minimizing the transfer of force generated during exercise to the station.

Advanced resistive exercise device is used to maintain skeletal health and also muscular strength and endurance (85). It has been operationally available since early 2009 and offers increased functional performance over its predecessor, the interim resistive exercise device (maximum load of 135 kg) (126). Advanced resistive exercise device uses 2 vacuum cylinders (constant external resistance) and flywheels (inertial loading) to mimic free weight exercise. Advanced resistive exercise device accommodates individuals from the fifth to 95th percentile in size and offers loads ranging from 5 to 273 kg through use of the main arm assembly. An exercise cable offers focused upper-body and lower-body strength training at loads ranging from 5 to 68 kg. Hardware attachments include an exercise bench with belt, heel-raise platform, cable pull bar, cable pull handles, and ankle cuffs. Custom ARED software receives prescriptions from the ground, displays the workout to the crewmember, and records data. The data acquisition system on ARED was designed to provide repetition counts, sets completed, static and dynamic load measurements, and exercise start and stop times. Because of malfunctions in the instrumentation system, these data are currently self-reported. A new instrumentation box is slated to arrive at the ISS and will return power to the ARED instrumentation and data acquisition systems in 2015. Both a force-plate redesign and portable load-monitoring devices are under consideration as means to measure exercise loads, more accurately track resistance exercise performance, and accommodate biomechanical analyses.

Cycle ergometer with vibration isolation system was installed on the ISS in early 2001 to provide aerobic and

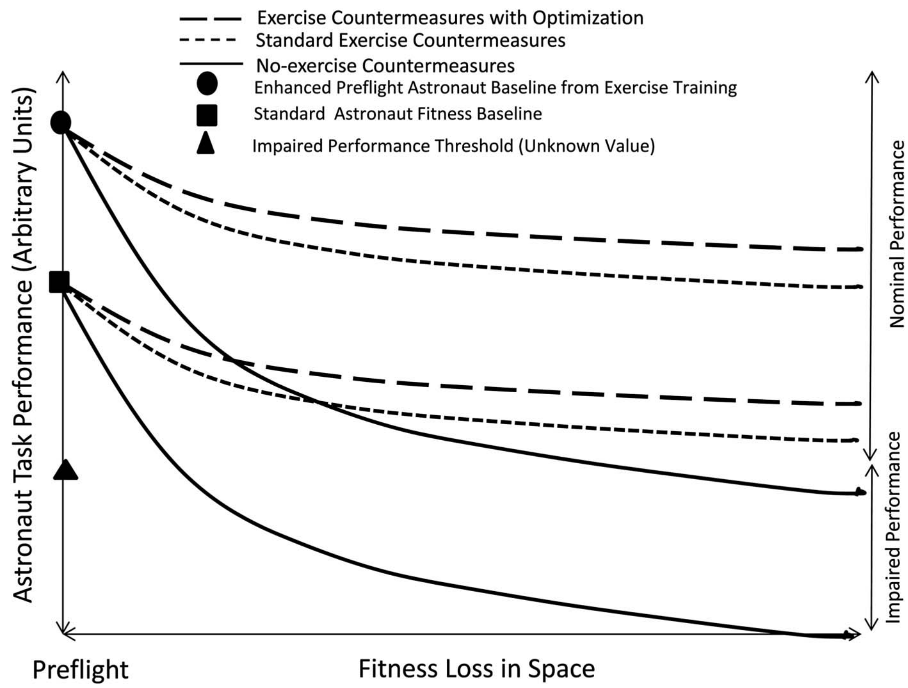

Figure 1. Modeled relationship between astronaut task performance and fitness loss in space. "No-exercise countermeasures" is a hypothetical situation given exercise in space is a medical requirement for U.S. crewmembers. "Standard exercise countermeasures" refers to Astronaut Strength, Conditioning, and Rehabilitation specialist (ASCR) exercise prescription without additonal optimization. "Optimization" refers to enhanced nutritional or pharmaceutical support of ASCR exercise prescription to enhance performance.

cardiovascular conditioning; it is also used to conduct periodic fitness evaluations of aerobic capacity. Cycle ergometer with vibration isolation system operates from 0 to 350 W and allows pedal speeds from 0 to 125 revolutions per minute. Exercise prescriptions are uploaded to the control panel, and data are downloaded by ground personnel through the station's network server. The control panel records resistance, speed, and torque, from which power output can be calculated. An integrated heart rate monitor synchronizes performance data with heart rate.

The T2 was installed on the ISS in 2010. Second-generation treadmill, which replaced the treadmill with vibration isolation system, was derived from a commercial Woodway Path treadmill and has a redesigned passive vibration isolation system. Improved functional capabilities include a greater maximum speed (up to 5.5 $m \cdot s^{-1}$). Use at low speed results in significant instability and tends to saturate the vibration isolation system and impart higher-than-desired loads to the vehicle, so crews are limited to operating at $\geq$1.3 $m \cdot s^{-1}$.

Exercise Monitoring and Prescription

Historically both on the ground and during flight exercise has been challenging to document in detail. Preflight exercise training is prescribed by an ASCR and is included in the astronauts' daily schedules. Astronauts are encouraged to wear heart rate monitors and keep exercise logs during preflight training, but this is not a requirement. Tracking and management of in-flight exercise data are similarly challenging. Astronaut Strength, Conditioning, and Rehabilitation specialists develop in-flight exercise prescriptions based on individual fitness parameters (e.g., peak cycle tests performed 60–90 days before launch, and ground ARED training sessions) and previous experience working with individuals in microgravity. Although crewmembers complete preflight familiarization sessions on ground training units of the ISS exercise hardware, these devices are designed for use in a reduced gravity environment, and thus, they are not optimized for daily exercise training in earth's gravity. As such, most preflight training is performed on traditional exercise equipment.

In-flight ARED exercise prescriptions are developed during these preflight training sessions performed on an ARED ground unit. Early mission resistance exercise prescriptions are relatively conservative to provide acclimatization to loading in a microgravity environment. Because a crewmember's body mass does not contribute substantial resistance in microgravity, this must be added to the external load. For example, an 80 kg crewmember that squats 100 kg would need to load the ARED bar to 180 kg to attain

Table 2. U.S. exercise hardware across the eras of space missions.*†

Mercury (1959–1968)	Gemini (1961–1966)	Apollo (1961–1972)	Skylab (1965–1979)	Shuttle (1972–2011)	Shuttle-Mir (1995–1998)	ISS (1993–present)
None	Bungee exerciser‡	Exer-genie	Cycle ergometer	Cycle ergometer	Cycle ergometer	CEVIS
		Cycle§ ergometer	Teflon treadmill	Passive treadmill	EDO Treadmill	TVIS
			MKI/mini gym MKII	EDO treadmill EDO Rower		iRED ARED‖ T2¶

*ISS = International Space Station; CEVIS = cycle ergometer with vibration isolation system; EDO = extended duration orbiter; TVIS = treadmill with vibration isolation system; MKI/mini gym = isokinetic rope and pull device; iRED = interim resistive exercise device; MKII = handle and spring assembled exercise device; ARED = advanced resistive exercise device; T2 = second-generation treadmill.

†All information adapted from Refs. 6,122. Adaptations are themselves works protected by copyright. So in order to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

‡Gemini IV only.

§Dropped because of weight constraints.

‖Available 2009.

¶Available 2010.

a similar static load. However, unlike on earth, the entire load is directed through the shoulders down the axial skeleton; this musculature is unable to support such high loads (19). As a result, during flight, the ASCRs monitor individual crewmember exercise form, performance, and comfort level to adjust exercise prescription.

The current ISS exercise equipment was designed to provide basic performance monitoring. For example, T2 and CEVIS have integrated heart rate monitoring capabilities and require crewmembers to do a chest strap to transmit heart rate data to the integrated receiver. Users operate the treadmill from a laptop computer and custom software interface. The treadmill operates in either a powered or a nonmotorized passive mode. The T2 logs data from sensors and accelerometers located under the treadmill surface from which ground reaction forces can be derived. The T2 also records belt speed, resistance, and start and stop times. After each exercise session, the crewmember logs off of the control panel and the data are then pushed to T2's central computer, from which ground personnel downlink these data. Wrist watches are used as the backup data-logging method when the primary system is not available. The watch files are manually downloaded to a laptop computer and these data are downlinked to the ground for analysis.

From a science perspective, exercise data are classified as protected medical information and require special permission for research use. Investigators have obtained data-sharing agreements and subsequently reported their findings (51,126,146). The quality of the exercise data has sometimes suffered given issues, such as instrumentation malfunction, downlink interruption, software bugs, and operator error. At times, researchers evaluating exercise-based outcomes from in-flight studies are forced to make assumptions on exercise performance (e.g., repetitions, work load, number of muscle contractions, calorie intake, and expenditure) based on crewmember recall.

Monitoring astronauts' exercise performance (as an indicator of spaceflight-induced deconditioning) will be more important than ever on missions beyond low earth orbit. On earth, consumer demand for performance-enhancing technologies and training tools has led to market availability of instrumented footwear, high-tech sports watches, activity monitors, and interactive gaming systems. These devices allow data to be logged and shared through wireless interactive networks. As these types of technologies mature and advance in robustness, they may warrant consideration for use by crewmembers during in-flight exercise. These tools could enhance the in-flight training experience and provide ASCRs and/or researchers with invaluable performance information to enhance the efficacy and efficiency of spaceflight exercise. Furthermore, although aerobic capacity can be tested in-flight (90), there is currently no reliable means of testing muscular strength as traditional strength tests such as the one-repetition maximum are considered too risky to perform in spaceflight. Potential candidates to facilitate in-flight strength testing are the muscle atrophy research and exercise system, a dynamometer that was developed by the European Space Agency (39), and force sensing shoes that could be worn during the performance of maximal isometric movements on ARED (e.g., a mid-thigh pull).

Currently, crewmembers are scheduled 2.5 $h \cdot d^{-1}$ of exercise, 6–7 $d \cdot wk^{-1}$ (20,126,146). Aerobic exercise is prescribed 6 $d \cdot wk^{-1}$ and is performed on either CEVIS or T2. Crews are assigned 60 minutes for aerobic exercise, which also

Figure 2. The advanced resistive exercise device (ARED). Photograph courtesy of National Aeronautics and Space Administration.

Figure 3. The cycle ergometer with vibration isolation system (CEVIS). Photograph courtesy of National Aeronautics and Space Administration.

includes data transfer and cleanup. Crewmembers are allotted 90 minutes for ARED sessions but, as with athletes on earth, only 40–60 minutes is spent on actual exercise with the remaining time consumed by equipment setup, hardware inspections, and transitions between exercises, data logging, stowage, and cleanup. Because crew time is at a premium, it is important to understand the minimum amount of exercise time required to maintain physical function. This will require sound scientific evidence demonstrating that shorter exercise prescriptions can elicit positive outcomes in musculoskeletal and cardiovascular systems. The recent hardware upgrades have permitted increases in exercise intensity, and research is underway to determine how to safely reduce time spent on resistance and aerobic exercise. Exercise is a psychological countermeasure as well; thus, it is also important to understand the amount of exercise time required for behavioral health benefits. It is certainly possible that physical function may be maintained with short episodes of high-intensity exercise, but that psychological benefits may require additional exercise. Nevertheless, understanding how to maximize the efficiency of exercise is critical.

Numerous studies demonstrate that higher intensity exercise prescriptions result in positive musculoskeletal and cardiovascular adaptations (17,48,49,57,154). This concept has been applied to spaceflight exercise prescriptions, especially given the enhanced capabilities of ARED. Most recently, the Integrated Resistance and Aerobic Training Study (SPRINT) has formally emphasized high intensity for both resistance and aerobic exercise across the duration of the mission (107). The exercise prescriptions for this study were influenced by (a) a series of detraining studies that showed exercise intensity was the most important factor for maintaining fitness (60,61); (b) evidence demonstrating that intervals of short (20–30 seconds) (17,48,49), medium (2 minutes) (52,81), and long duration (4 minutes) (57,154) were efficacious in improving fitness; and (c) unloading studies (bed rest and limb suspension) suggesting that lower frequency ($3\ d\cdot wk^{-1}$) resistance exercise could maintain muscle mass and strength (5,119). Participation by crewmembers in SPRINT is voluntary. Once enrolled in the study, crewmembers are asked to keep detailed records of exercise performed both before and during flight, participate in acquisition of dependent variables (e.g., MRI, muscle function and $\dot{V}O_2$peak), and adhere to study constraints (e.g., a minimum of 4 hours between resistance and aerobic sessions). The results from SPRINT will enhance the understanding of how exercise hardware capabilities and exercise prescriptions interact to prevent physiological deconditioning during long-duration spaceflight.

Figure 4. The second-generation treadmill (T2). Photograph courtesy of National Aeronautics and Space Administration.

Factors Influencing Exercise Countermeasures Efficacy

Energy Intake and Macronutrient Composition

The history of nutrition during exposure to microgravity is well documented (100,129,131,135). Energy and water are the essential human consumables; they influence numerous physiological systems and are primary contributors to the overall health of the human body. An exhaustive discussion of this topic is beyond the scope of this review. Thus, an emphasis will be placed on total energy intake and the composition of macronutrients ingested during spaceflight. The requirements for energy intake in space are based on equations established by the World Health Organization (WHO), assuming moderate levels of activity. Macronutrient requirements are based on a percentage of the total energy intake and are 12–15% protein, 50–55% carbohydrate, and 30–35% fat (70–72,129).

During the Skylab program (1973–1974), extensive metabolic data were collected during missions lasting 28, 59, and 84 days (63). To date, the data obtained during these missions represent much of what is known about energy intake and expenditure during prolonged exposure to microgravity. Crewmembers were asked to eat their formulated diet for 21 days before flight, throughout the flight, and for 18 days on their return (63). Crewmembers during the Skylab missions thus consumed 99% of the WHO recommendations (72) with protein, carbohydrate, and fat constituting 15, 58, and 26% of their energy intake, respectively (72). These data demonstrate that when food intake is mandated, crewmembers are capable of meeting the WHO recommendations. However, the postflight comments of the Skylab astronauts regarding the required food intake were so negative that this practice has not been repeated (135). Since the Skylab missions, a voluntary reduction in energy intake has been a consistent finding during space missions. Lane et al. (72) summarized energy intake from crewmembers on all missions (n = 33) up to 1994 and found that astronauts averaged 7,864 $kJ \cdot d^{-1}$, which was only 64% of the WHO recommendations. Macronutrient intake for protein, carbohydrate, and fat during this period was 16, 58, and 28%, respectively. According to reports, few complaints were made about the food quality or choices during U.S. Space Shuttle missions (72); however, crewmembers may have had limited time to consume food because of their rigorous schedules (72). On missions of longer duration, Stein et al. (139) reported that crewmembers consumed 11,946 $kJ \cdot day^{-1}$ which was ~78% of their preflight value. More recently on the ISS, Smith et al. (130) showed mean energy intake during flight was 9,563 kJ per day, which was equivalent to ~80% of the WHO recommendations. Total protein intake was 102 ot29 $g \cdot d^{-1}$ (1.37 $g \cdot kg^{-1} \cdot d^{-1}$); carbohydrate and fat intake were not reported independently. Historically, total energy intake has been lower than recommended levels (136), which facilitates a loss of body weight at a rate of 2.4% per 100 days of spaceflight (88). However, more recent missions suggest that total energy intake is improving with resultant weight loss mitigation (126).

Aging and Anabolic Resistance

In studies that have examined astronauts and exercise countermeasures, subjects were on average 48 years of age (46,90,146). Between the ages of 20 and 70 years, muscle mass losses on earth range from 0.26 to 0.56% per year (30). This natural age-associated decrease in muscle mass may be problematic for astronauts for several reasons. First, a loss of contractile tissue results in decreased voluntary force production (22,23). Decreased strength is associated with impaired balance, functional decline (6,43,111,149), and falls (32,86,91,116). Falls may also be linked to the loss of muscle power (i.e., the ability to produce force rapidly) (59). Therefore, an older astronaut may have less baseline (preflight) strength and power than a younger counterpart. A second and more subtle consequence of age-related muscle loss is its effect on metabolism (155). Skeletal muscle tissue is the largest endogenous source of amino acids, which are essential to the synthesis of new proteins and immune function. Skeletal muscle is also a primary target of insulin and the largest reservoir of glucose (in the form of glycogen);

it is also a major site of oxidation of both glucose and free fatty acids from the systemic circulation (155). Large decreases in muscle mass can have deleterious consequences for systemic homeostasis and lead to the onset of metabolic disorders (26,141).

Aging also seems to exacerbate muscle loss during inactivity, as older adults lose muscle mass much more rapidly than their younger counterparts (40,67,97). The fundamental mechanisms of aging-related muscle loss are not well understood. Protein breakdown does not seem to be elevated in healthy older adults (151), and investigators have been largely unable to identify differences in basal (postabsorptive) muscle protein synthesis between young and elderly subjects (31,151). However, a number of studies have documented a diminished anabolic response in elderly subjects to feeding (31,65,66,150) and exercise (68), both potent anabolic stimuli. This blunted anabolic response has been termed "anabolic resistance" (104,115). Although astronauts are middle-aged adults, anabolic resistance may be a contributing mechanism underlying spaceflight-induced muscle loss. Furthermore, although muscle loss during disuse seems to be driven primarily by a reduction in muscle protein synthesis (67,96,144), this is still vigorously debated (105,114). Muscle protein breakdown is largely unaltered by bed rest in young adults (41,144); however, we lack corresponding data in older populations. Although an increase in breakdown of muscle protein would be consistent with the accelerated loss of muscle mass in older adults, anabolic resistance (104,115) or a blunted protein synthetic response to mixed nutrient meals is likely to play a much greater role (150). Supporting data have also been reported by researchers using a 14-day unilateral knee immobilization protocol (50). In a cohort of young, healthy subjects, postabsorptive basal muscle protein synthesis in the vastus lateralis of the immobilized leg fell by 27%. Furthermore, the nonimmobilized leg had an increase in muscle protein synthesis that was as much as 68% greater than the response of the immobilized leg to available amino acids. The authors concluded that both the decrease in postabsorptive muscle protein synthesis and the impaired postprandial response cause the muscle loss that occurs during immobilization (50). Similar changes may explain a large portion of the muscle loss with spaceflight.

Enhancement of In-flight Exercise Countermeasures

Energy Intake

Increasing voluntary energy intake to the WHO-recommended level has been suggested as an important step toward improving crewmember health (130) and enhancing the effectiveness of near-daily resistance and aerobic exercise. Stein et al. (135) suggest several possible reasons for the reduced intake, which include (a) enhanced food processing that decreases food gratification, (b) altered gastrointestinal transit, (c) decreased satiety due to food not settling in the stomach, (d) thermoregulatory issues, and (e) higher ambient carbon dioxide levels. Given the difficulty of addressing all of these factors, it may be necessary to include dietary supplementation to assist with energy balance and increase performance capability.

Protein and Amino Acids

One consequence of reduced energy intake is a reduction of muscle protein synthesis, which may shift net protein balance (synthesis-degradation) to a negative state (10). Without adequate energy intake, exercise to prevent the loss of cardiac and skeletal muscle tissue may unintentionally exacerbate muscle tissue loss (136). Diets high in protein have been repeatedly demonstrated to protect lean mass during the negative energy balance of weight loss or intense training (64,74,82,92,98). During spaceflight, recommended protein intake is 12%–15% of total energy intake (70–72,129); in the Apollo, Skylab, Shuttle, and ISS programs, this has corresponded to a range of 0.8–1.6 $g \cdot kg^{-1} \cdot d^{-1}$ (136). Protein intakes of 102 $g \cdot d^{-1}$ (1.4 $g \cdot kg^{-1} \cdot d^{-1}$) have been documented on the ISS (130). Whether this is sufficient to maintain muscle size and strength during spaceflight has been discussed from both muscular and skeletal perspectives (54,135–137). For instance, bed rest and limb immobilization studies have explored the musculoskeletal effects of increased protein intake (35), the provision of branched-chain amino acids (138,140), essential amino acids (97,157), and the essential amino acid leucine alone (148) and the timing of essential amino acid intake relative to exercise (15). To date, neither protein-related nor amino acid-related countermeasures have been considered for in-flight implementation because of concerns over efficacy, cost of delivery to the ISS, and the potential association between elevated animal protein/sulfur-containing amino acid intake and markers of bone breakdown (54,157,158). Another aspect of protein intake with the potential to improve muscle outcomes in spaceflight is protein distribution across meals. In a ground-based study, evenly distributed protein intake (30 g per meal) elicited 25% higher rates of muscle protein synthesis over a 24-hour period than did a "skewed" protein intake (10, 15, and 65 g at the 3 daily meals, respectively) that is representative of typical American dietary practice (87). Together with other data which indicate that ~30 g of high-quality protein elicits a maximal anabolic response (145), meal-based protein prescription represents a payload-free strategy to potentially enhance the protective effect of protein that is already in the astronaut diet (73,95,156). Future research to explore the effects of protein distribution and protein/essential amino acid/leucine supplementation on the optimization of exercise countermeasures and muscle outcomes is warranted.

Phosphocreatine Intake

Phosphocreatine, in combination with the enzyme creatine kinase, is used as an immediate energy source to rapidly regenerate adenosine triphosphate for muscle contraction (14). Other hypothesized effects of phosphocreatine include

decreased blood levels of proinflammatory cytokines, an increase in satellite cell proliferation, and upregulation of genes for protein synthesis and cell repair (118). Phosphocreatine supplementation (5 $g \cdot d^{-1}$) in combination with resistance exercise training has been shown to increase muscle mass and strength in younger adults (33). Similar muscular improvements (34) and enhanced cognitive function have been reported in older adults (112). During upper-extremity immobilization, Johnston et al. (62) showed that consumption of creatine on days 15–21 of immobilization resulted in better maintenance of lean tissue (+1%), strength (−4%), and endurance (−10%) than placebo (−4, −22, −43%, respectively). Because creatine was not provided until the third week of immobilization, it is unknown if earlier supplementation could further attenuate muscle mass, strength, and endurance losses. In contrast, Hespel et al. showed that creatine supplementation was not effective to maintain muscle mass and power during 2 weeks of leg immobilization, but did improve rehabilitation outcomes (58). One limitation of these studies is the technique used to stimulate disuse atrophy and strength loss. Cast immobilization and the restriction of joint movement result in greater muscle atrophy and strength loss than unloading during limb suspension (55) or bed rest (21). Furthermore, neither of these 2 studies evaluated phosphocreatine intake with exercise, which is a critical catalyst for physiological adaptations. Further research coupling creatine supplementation and exercise countermeasures is needed in spaceflight analogs such as bed rest or limb suspension.

Vitamin D

To our knowledge, vitamin D (400–500 $IU \cdot d^{-1}$) is the only dietary supplement that has been supplied to astronauts during flight (124,130); this supplementation was introduced in response to declines of 25–36% in serum 25-hydroxy vitamin D concentrations during and after 3-month to 4-month flights (127,128,130). Vitamin D is known to be beneficial for calcium metabolism and bone tissue (9). However, with the discovery of vitamin D receptors in skeletal muscle (134), it is biologically plausible that vitamin D may play a role in muscle mass, strength, and performance, particularly in older adults (11,103,110). Currently, the relationship between in-flight vitamin D supplementation and in-flight and postflight serum vitamin D status is unclear (130). Also unknown is how supplementation influences muscle mass and strength during microgravity exposure.

Pharmaceutical Intervention

Evidence exploring anabolic hormone changes during spaceflight is difficult to interpret. Early data suggested that testosterone may be reduced with spaceflight (142); however, more recent studies do not support this conclusion (125). Serum cortisol and dehydroepiandrosterone were also unchanged during spaceflight in crewmembers (125), indicating that nonpharmacological approaches may be safer for the optimization of exercise countermeasures and human performance. Alternatively, it can be argued that pharmaceutical interventions must be considered as a realistic and potentially viable adjunct therapy during spaceflight. Exercising intensely 6–7 days a week for 6 months (and much longer for future Mars missions) is physically taxing, consumes energy stores and valuable crew time, and still is not 100% effective at protecting muscle strength and cardiovascular endurance for all astronauts. In addition, alternative approaches must be considered as contingencies for catastrophic exercise equipment failure. Pharmaceuticals such as myostatin inhibitors (89,123), testosterone (152), and selective androgen receptor modulators (8,120) are just a few candidate agents that may prove efficacious. These and others may warrant further investigation in analog research to determine the safety and efficacy of extended use during long-duration exploration missions.

Conclusion

The human body rapidly adapts to the microgravity environment, resulting in central and peripheral system impairments relative to the function of these systems on earth. Although astronauts do not perform exercise training for sport or competition, a strict dedication to aerobic and resistance exercise before and during spaceflight is important as a defense against impaired task performance. The answer to the central question of how much fitness is required for space mission success is still unknown and requires further work to elucidate the strength, power, and aerobic capacity thresholds associated with effective simulated astronaut task performance. Variables, such as energy intake and aging, also need to be considered to gain a better understanding of multilevel interactions that influence adaptation during spaceflight. Future research exploring exercise countermeasures with manipulation of vitamin D, protein/amino acid intake, and phosophocreatine supplementation represents the next stage of exploratory strategies to optimize exercise countermeasures and performance during spaceflight. Pharmaceutical approaches also must be considered, given the importance of successfully exploring deep space.

Practical Applications

Astronauts are a small group of occupational athletes who, like others in the tactical athlete population, need strength and conditioning programs tailored to the unique demands of their profession. These programs must be implemented both before and during spaceflight to ensure optimal performance and ultimately, mission success. Critical in this process is the identification of muscle strength/power and aerobic capacity thresholds below which mission task performance is likely to be impaired; such work has been successfully conducted in other tactical professions (e.g., fire, police, and military) and must be performed to maximize the potential for future mission success. Last, advances in spaceflight exercise monitoring and prescription and also research to characterize the potential benefits of various nutritional adjuncts and pharmaceuticals will serve to better

prepare and protect the astronaut-athlete during performance of their unique missions.

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