Physical Training for Long-Duration Spaceflight

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INTRODUCTION: Physical training has been conducted on the International Space Station (ISS) for the past 10 yr as a countermeasure to physiological deconditioning during spaceflight. Each member space agency has developed its own approach to creating and implementing physical training protocols for their astronauts. We have divided physical training into three distinct phases (preflight, in-flight, and postflight) and provided a description of each phase with its constraints and limitations. We also discuss how each member agency (NASA, ESA, CSA, and JAXA) prescribed physical training for their crewmembers during the first 10 yr of ISS operations. It is important to understand the operational environment, the agency responsible for the physical training program, and the constraints and limitations associated with spaceflight to accurately design and implement exercise training or interpret the exercise data collected on ISS. As exploration missions move forward, resolving agency differences in physical training programs will become important to maximizing the effectiveness of exercise as a countermeasure and minimizing any mission impacts.

KEYWORDS: physiologic deconditioning, exercise training.

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Spaceflight results in musculoskeletal and cardiovascular deconditioning as well as sensorimotor dysfunction and physical training (PT) has been employed as one method to counter these undesirable physiological adaptations. Each member space agency of the International Space Station (ISS) has its own approach to developing physical training protocols for their astronauts. NASA has two specific groups within the Space and Clinical Operations Division that share responsibility for astronaut PT: the flight surgeons and the Astronaut Strength, Conditioning & Rehabilitation (ASCR) group. The physiological countermeasure specialists and flight surgeons in the medical operations group of the Japan Aerospace Exploration Agency (JAXA) with the ASCRs are responsible for providing PT for the Japanese astronauts. The Canadian Space Agency (CSA) medical operations support team and the European Space Agency (ESA) space medicine office consist of flight surgeons, exercise specialists, and biomedical engineers. The PT support between the various international partners is coordinated through the ISS Multilateral Medical Operations Panel.

Astronauts scheduled for flights aboard the ISS trained in the U.S., Russia, Europe, Japan, and Canada. Astronauts were assigned to an ISS mission approximately 2 yr before flight. As part of their training flow, each astronaut had PT scheduled weekly to prepare them for the demands of their mission and reconditioning activities following their mission. The PT was broken into three distinct phases: 1) preflight–to prepare the crew for their mission; in-flight–to maintain crew health and meet the physical demands during and after their mission; and postflight–to return the astronaut to their preflight physical capacity. The international nature of the ISS and its crew resulted in both differences and similarities in the approach each agency had for PT. Herein we describe each phase of conditioning, limitations that affected PT, and how each agency (NASA, ESA, CSA, and JAXA) prescribed PT for their crewmembers during the first 10 yr of ISS habitation.

PREFLIGHT EXERCISE

Each crewmember was allotted 4 h • wk^{-1} for PT in their overall training flow. The PT schedules were predominantly based upon two factors: crew preference and the ability of the crew scheduler to place PT in the training flow. There was no

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requirement for how these 4 h were allocated (e.g., one 4-h block, four 1-h blocks) and the allocation could vary from week to week. Any additional exercise was performed outside the scheduled training.

Several limitations affected preflight PT. Extremely busy training schedules, especially before mission launch, resulted in inconsistent preflight training. Total scheduled work hours per week were limited with the result that PT was often the first activity deleted from the training schedule based on priority. International travel added additional complications with multiple facilities, varied exercise equipment at each facility, jet lag, and varied lengths of stay and scheduling constraints in each country. Finally, family obligations must be considered when assessing PT limitations. Taken together, these multiple factors made it difficult to maintain a consistent preflight exercise routine.

NASA

NASA's preflight training programs included appropriate exercises that produced outcomes specific to individual crewmember needs, taking into account biomechanical and physiological differences, age, initial training status, and overall health with the goal of maximizing physical capabilities before flight. Cardiovascular training was recommended at least 3 to 5 $d \bullet wk^{-1}$, exercising at 65–95% heart-rate maximum for 20 to 60 min and consisted of steady state and interval running, cycling, rowing, swimming, stepping, and elliptical exercise. Resistance exercise was recommended 2 to 3 $d \bullet wk^{-1}$. The preflight weight training program used a straight linear periodization, starting with a general training phase, followed by a strength phase, a power phase, and a muscle endurance phase (stamina) while focusing on multiplanar/multijoint functional movements. The purpose for prescribing exercises in this fashion was to teach proper technique and focus on movement patterns rather than specific muscles. This method ensured all potential movement patterns met the performance demands in flight, making the transfer of strength and power easier to merge with the development of skills. A sample list of exercises is shown in **Table I** and the template for prescription design is shown in **Table II**.

JAXA

Upon assignment to a specific ISS mission, Japanese astronauts participated in a supervised preflight exercise program to optimize their physical condition before the mission and prepare them for physically demanding mission specific tasks. JAXA recommended its astronauts exercise 2 to 3 $d \bullet wk^{-1}$ for 2 $h \bullet d^{-1}$ beginning no less than 1 yr before launch (**Table III**). JAXA's physiological countermeasures team individualized preflight exercise programs for each astronaut according to their measured fitness levels and anticipated mission tasks. The preflight training program consisted of aerobic and muscle strength training with specific arm muscle strength and endurance training for astronauts scheduled to perform extravehicular activity. The JAXA astronauts trained at the Johnson Space Center in Houston with supervision by the ASCRs. Weekly exercise logs for each astronaut were sent electronically to the JAXA physiological countermeasures team, enabling them to track and modify the exercise prescriptions as necessary.

CSA

The primary preflight PT objective for Canadian astronauts was to ensure general physical preparedness so that the astronaut would be able to conduct mission operations safely and effectively while maintaining a sufficient reserve to help offset the known deconditioning effects of spaceflight. An additional objective was to ensure that the crewmember was trained and familiar with in-flight equipment, exercise techniques, and protocols. Because CSA astronauts were physically based in Houston, the CSA exercise specialist usually met with the crewmember every 6 to 8 wk to update the preflight PT program. In between face-to-face meetings, PT was monitored using heart-rate data and electronic journals. Workouts were updated remotely as needed, with support provided by ASCRs.

The preflight PT program consisted of resistance, cardiorespiratory, flexibility, balance, and agility exercises. The resistance exercise program was recommended to be performed 3 $d \bullet wk^{-1}$ and was based on the maximum load that could be lifted once (1 RM). The program consisted of 3 phases, each phase lasting 4 wk: 1) focused on joint stability and muscular endurance (60% to70% 1 RM; 12 to 20 repetitions; 1 to 3 sets); 2) focused on strength and hypertrophy (70–85% 1 RM; 6 to 12 repetitions; 2 to 5 sets); and 3) focused on alternating between endurance, strength, and power. Following the completion of phase 3, the crewmember was provided with new exercises and repeated the 3 phases. Preflight cardiorespiratory conditioning consisted of steady state and interval stimulus training 3 to 5 $d \bullet wk^{-1}$. Protocols and exercises planned for use during in-flight PT were gradually incorporated into the preflight exercise routine.

ESA

Preflight conditioning and training was a key element for successful in-flight support. The ESA exercise specialists, physiotherapists, and flight surgeons provided health and medical support at an early stage; however, due to European astronaut travel schedules, frequent in-person support was limited and most communication was conducted through remote interaction. International cooperation thus was an important element to ensure ESA astronauts received sufficient guidance during PT and in the use of ISS exercise training hardware. There were two goals within the preflight phase: 1) to

Table I. Sample List of NASA's Preflight Resistance Training Exercises.

SQUATS	DEADLIFTS	PRESSES	PULLS	ADDITIONAL EXERCISES	AEROBIC CONDITIONING
Back	Deadlift	Shoulder Press	Pullups	Kettlebell Exercises	Running
Front	Sumo Deadlift	Push Press	Bentover Rows	Medicine Ball Exercises	Swimming
Overhead	Romanian Deadlift	Bench Press	Upright Rows	Power Clean/Hi-pull	Cycling
Sumo		Pushups			Rowing
Single Leg		Dips			Elliptical
					Stepping

Table II. NASA's Preflight Resistance Training Template.

CYCLE	SETS	REPS
General Training	3	10–12
Strength	3–4	8–10
Power	4	5–6
Muscle Endurance	3–4	15+

adequately prepare the astronaut to perform a safe training program on ISS, and provide a baseline to efficiently monitor pre- and in-flight performance; and 2) to provide an efficient long-term health program, preventing diseases through supporting an active, healthy lifestyle. In preparation for a long-duration mission, training focus shifted toward in-flight countermeasure training, whereas unassigned crewmembers pursued a general active health and well-being concept. The ESA astronauts trained 4 h • wk^{-1} including resistance and aerobic exercise as well as sports such as climbing or game sports.

IN-FLIGHT EXERCISE

During the mission, each crewmember was scheduled for 2.5 h of PT 6 d • wk^{-1}: 1.5 h • d^{-1} of resistance exercise, and 1 h • d^{-1} of cardiovascular exercise. Most astronauts performed PT on the seventh day even though it was considered a rest day. The allotted exercise time included time for changing into exercise clothes, postexercise hygiene, and hardware set-up and stowage. Resistance exercise was initially performed with the interim resistive exercise device (iRED) and currently is performed using the advanced resistive exercise device (ARED). Cardiovascular exercise was performed using a treadmill (treadmill with vibration isolation system [TVIS]; the second-generation treadmill [T2/COLBERT]) or a cycle ergometer (cycle ergometer with vibration isolation system [CEVIS]; Russian Velo-ergometer).

In addition to regular PT exercise, a monthly fitness assessment was performed on CEVIS to monitor changes in cardiovascular fitness and video recordings were used to monitor treadmill and resistance exercise technique for safety and efficacy. Resistance exercise video was recorded within the first 14 d and then once a month for the remainder of the mission while treadmill video was taken at 30 d and 60 to 90 d into the mission.

Table III. JAXA's Preflight Exercise Program.

1. Time and frequency of preflight training
a. 2 h per day, 3 d a week
b. Beginning not less than 1 yr before launch
2. Objective of preflight training
a. Reach optimal physical condition before the mission
b. Prepare for any physically demanding mission tasks
3. Program menu
a. Aerobic
b. Muscle strength
c. Endurance training
4. Training for extravehicular activity
a. Plan muscle strength and endurance training of upper extremity

Many limitations impacted PT during flight and they were not always remedied in a timely manner. Complete or partial hardware failures resulted in exercise limitations/modifications that necessitated real-time adaptation with the understanding that the hardware might not be repaired for months or even years. Flight operations occasionally restricted exercise due to vibration sensitive experiments, maintenance activities, and/or extravehicular activity. In addition, the crew schedule itself affected PT; for example, 1.5 h of resistance exercise for 6 crewmembers equals a total of 9 h; the crew workday is only 8 h. Furthermore, PT was deferred if planned operational activities exceeded their allotted time in the daily planning schedule. Communication was another major limitation due to a lack of real-time feedback, limited private conferences and slow turnaround time for email and exercise data. Any updates to the exercise program due to injury, crew deviation from the prescription, or crew feedback required several days to a week to implement. These limitations and their potential negative impact on crew health should be considered when developing or evaluating the effectiveness of in-flight exercise prescriptions for long-duration spaceflight.

NASA

The in-flight PT program was designed to maintain or minimize the loss of bone mineral density, aerobic and anaerobic capacity, muscle strength, muscle power, and local muscle endurance, as well as minimize neuromuscular dysfunction. In-flight exercise focused primarily on the lower body (squat, deadlift, heel raise) because the majority of physiological adaptations during long-duration spaceflight occur in the lower body.

During Expeditions 1 through 20, the ASCRs recommended treadmill exercise 4 d • wk^{-1} and cycle ergometer exercise 2 d • wk^{-1}. This recommendation was altered in some instances to accommodate crew preference or pre-existing medical or hardware conditions that limited use of certain hardware. A list of steady state and interval cycle ergometer exercise protocols was prescribed for each crewmember based on the maximum oxygen consumption ($\dot{V}O_{2max}$) measured during a preflight graded-cycle-ergometer test (**Table IV**). Treadmill exercise prescriptions were self-selected by the astronauts, but they were urged to perform both steady state and interval exercise protocols. Treadmill exercise also was performed in both motorized and nonmotorized modes. During treadmill exercise, a harness was used to apply an external load to the astronaut; the initial load prescribed was approximately 60% of body weight for each astronaut. The external load was increased throughout the mission with the goal of reaching 100% body weight by the end of the mission. Unfortunately, high loads ($\geq$ 85%) were extremely uncomfortable and could not be tolerated by most crewmembers. In-flight treadmill exercise was difficult to prescribe given the lack of information regarding the effect of varying external loads and treadmill speeds on measures of cardiovascular conditioning during exercise. This coupled with the fact that interval protocols were limited by the maximum TVIS belt speed of 16.1 kph (10 mph) made it difficult to establish protocols to maximize the cardiovascular benefit expected from treadmill exercise.

Table IV. NASA's Expeditions 1–20 Sample CEVIS Exercise Protocols.

GREENLEAF PROTOCOL			TOUR DE ISS PROTOCOL		
Elapsed Time	Stage Time	% $\dot{V}O_{2max}$	Elapsed Time	Stage Time	% $\dot{V}O_{2max}$
7	7	40	2	2	40
9	2	60	4	2	60
11	2	40	6	2	70
13	2	70	8	2	80
15	2	40	10	2	85
17	2	80	12	2	60
19	2	40	14	2	75
21	2	90	16	2	85
23	2	40	18	2	90
25	2	80	20	2	85
30	5	40	22	2	60
			24	2	70
SIMPLE RIDE PROTOCOL			26	2	80
Elapsed Time	Stage Time	% $\dot{V}O_{2max}$	28	2	85
5	5	40	30	2	70
25	20	80	32	2	40
30	5	40			
ARM ERGOMETRY PROTOCOL					
Elapsed Time	Stage Time	Watts			
1	1	75			
4	3	150			

Resistance exercise performed using the iRED (Expeditions 1–18) was divided into a 2-session cycle consisting of upper body exercises and alternating double leg and single leg exercises (**Table V**). Light to moderate intensity exercise was prescribed during the first 2 wk to allow for acclimation to exercising in microgravity. The iRED maximum load was limited to 136 kg (300 lb), which precluded designing a true periodized protocol. For example, the iRED would provide a 90.9-kg (200 lb) astronaut exercising in microgravity a maximum of approximately 45.5 kg (100 lb) of external load after taking initial body weight into consideration.[2] To work around the load limitation, single leg exercises were incorporated into the exercise routine to increase the load applied to the lower body and exercise volume was dramatically increased in an attempt to provide an adequate stimulus (Table V). ASCRs developed the exercise prescriptions and modified them based upon weekly exercise logs, crew comments, and hardware failures or limitations.

During Expeditions 20–25, the cycle ergometers remained the same, but the TVIS was replaced with a new treadmill, designated T2. The harness used to provide loading during T2 exercise was similar to TVIS and had the same comfort limitations. The recommendation to partition aerobic sessions between the treadmill and cycle ergometer, treadmill loading recommendations, and the basic structure of performing steady state and interval protocols remained the same. However, the CEVIS protocols were updated to increase the intensity of the preprogrammed protocols and new interval protocols were added (**Table VI**). The increased maximum belt speed of 19.3 kph (12 mph) and the ability to upload preprogrammed protocols to T2 allowed for an increase in interval protocol intensity (**Table VII**).

Table V. NASA's Expeditions 1–18 Sample iRED Exercise Program.

MISSION TIMELINE (MO)	SETS	REPS	LOAD	SESSION 1, 3, 5	SESSION 2, 4, 6
First 2 wk	3	6–12	Varied	Deadlift	Single Leg Squat
1–2	3–5	6–12	Varied	Squat	Heel Raise
3–4	6–8	12–16	Varied	Single Leg Heel Raise	Romanian Deadlift
5–6	9–10	16–20	Varied	Upright Row	Bent Over Row/Bicep Curl

During Expedition 18, the iRED was replaced with an upgraded resistance exercise device, ARED, designed to fix the limitations of iRED.[3] With an increased load capacity of 272 kg (600 lb), volume and intensity were manipulated throughout an entire expedition, allowing for a periodized protocol. The ARED in-flight protocol was divided into two distinct 3-mo macro cycles (**Table VIIIA**), RM loads in the second macro cycle were increased based on values obtained from the final weeks of the first macro cycle, and each cycle was comprised of 3 individual exercise sessions that repeated and rotated throughout the protocol (**Table VIIIB**). For the lower body, the exercise sessions consisted of a light day (4 × 12 repetitions), heavy day (4 × 6 repetitions), and medium day (4 × 8 repetitions) with the loads based on a percentage of an estimated 1 RM. Heel raise exercises followed the same loading pattern but the repetitions were altered to increase the amount of work performed by the calves (4 × 12 repetitions). After the first 3 exercise sessions were completed, the order rotated to ensure each exercise session received a heavy, light, and medium day. All upper body exercises were completed at 3 × 10 repetitions. A warm-up set (1 × 10 to 12 repetitions) was included before the performance of the primary exercises. The primary exercises were lower body/triple extension movements using a variety of squat and deadlift stances to accentuate force production at different joint angles. Due to hardware limitations on speed of movement, high velocity exercises were not incorporated into the resistance exercise program. The initial loads were determined based upon preflight ARED training sessions. For the lower body, 6, 8, and 12 RMs were calculated from a 10 RM and 75% of the astronaut's body weight was added to all squat and heel raise resistance loads to compensate for the loss of body weight in microgravity.

JAXA

A well-conditioned crew must be balanced in all aspects of fitness to meet the rigorous mission demands and counteract the adverse effects of microgravity. In-flight exercise was important to astronaut fitness, health, quality of life, and preservation of biological rhythms. Physical exercise enhanced the quality of life and increased productivity, psychological well-being, and physical performance.

Generally, the Japanese astronauts performed 3 treadmill-exercise sessions per week and 3 cycle-ergometer exercise sessions per week for 30 to 45 min each (**Fig. 1**). In the beginning of the mission, cycle-ergometer exercise was performed more

Table VI. NASA's Expeditions 20–25 Sample CEVIS Protocols.

FITNESS ASSESSMENT PLUS WORKOUT

Elapsed Time	Stage Time	% $\dot{V}O_{2max}$
5	5	25
10	5	50
15	5	75
17	2	60
19	2	80
21	2	60
23	2	90
25	2	60
27	2	90
29	2	60
31	2	80
33	5	50

Note: First 3 stages are fitness assessment. Do not alter.

TOUR DE ISS PROTOCOL

Elapsed Time	Stage Time	% $\dot{V}O_{2max}$
2	2	50
4	2	60
6	2	75
8	2	85
11	3	60
13	2	75
15	2	90
18	3	60
20	2	90
22	2	75
25	3	60
27	2	85
29	2	75
31	2	80
33	2	70
35	2	55

MODIFIED GREENLEAF PROTOCOL

Elapsed Time	Stage Time	% $\dot{V}O_{2max}$
5	5	60
7	2	70
9	2	60
11	2	80
13	2	60
15	2	90
17	2	60
19	2	90
21	2	60
23	2	80
28	5	60

SIMPLE RIDE PROTOCOL

Elapsed Time	Stage Time	% $\dot{V}O_{2max}$
3	3	55
28	25	75
31	3	55

HILL PROTOCOL

Elapsed Time	Stage Time	% $\dot{V}O_{2max}$
4	4	60
8	4	70
12	4	80
16	4	70
20	4	60
24	4	70
28	4	80
32	4	70
36	4	60

ARM ERGOMETRY PROTOCOL

Elapsed Time	Stage Time	Watts
1	1	75
4	3	150

often to preserve the physical strength and aerobic capacity of the astronaut through the midpoint of the mission. In the latter phases of the mission, running sessions on the treadmill were performed every day to prepare for reambulation upon return to gravity. Updates to the in-flight exercise program (type of exercise, training load, and training time) occurred throughout the mission according to the periodic fitness evaluations performed once a month. Cycle ergometer exercise consisted of steady state and interval training programs designed to target 50–90% heart rate max or Borg's scale 13 (somewhat hard).[1] During treadmill exercise, 60–100% body weight load was applied to the astronaut by use of a harness and loading system as previously described. Crewmembers performed steady state and interval protocols, between 5 to 14.5 kph (3.1 to 9 mph), to target 60–80% heart-rate max, or Borg's scale 13 (somewhat hard).[1]

Resistive exercise training sessions were performed 6 $d \bullet wk^{-1}$ on the ARED. The Japanese crewmembers performed bar exercises (deadlift, heel raise, squat, bench press, etc.) and cable exercises (cable biceps and triceps, bent-over row, etc.) throughout the mission. The ARED training program consisted of lower and upper body exercises using 6, 8, and 12 RM loads for 4 sets to prevent muscle and bone atrophy. Specific ARED exercises were performed on alternate days to avoid muscle overuse injuries.

CSA

The objective of the in-flight program was to mitigate the deleterious effects of microgravity (musculoskeletal, cardiovascular and neurosensory deconditioning), ensuring operational effectiveness and decreasing the time required for postflight reconditioning. The primary hardware used for in-flight exercise included the CEVIS, TVIS, and ARED.

The resistance exercise program was composed of two phases: 1) to allow the crewmember to adjust to the microgravity environment and determine appropriate loads for resistance training and 2) to mitigate the effects of microgravity. Phase 1 of the resistance program was conducted during the first 3 wk of flight and consisted of three different workouts. Each workout was composed of a warm-up set and 2 to 3 working sets of 10 repetitions with an emphasis on lower body exercises (squats, deadlifts, heel raises). The initial starting loads for all exercises except squats and heel raises were estimated to be 65% of the crewmember's ground-based load. The starting loads for squats and heel raises were estimated as their ground-based load plus 65% of their body weight. Phase 2 was based on the NASA in-flight ARED program (Table VIII) and consisted of three workouts and three variations of loading (light, medium, and heavy). However, unlike the NASA program, loads were increased by 5% approximately every 3 wk provided all loads during that period were completed as prescribed. A warm-up set (1×8 repetitions) was performed before each exercise.

The cardiorespiratory program consisted of steady state and interval protocols using the cycle ergometer or treadmill to maintain aerobic fitness at or above 75% of the preflight value. CEVIS protocols were based on a preflight maximum oxygen consumption ($\dot{V}O_{2max}$) graded cycle ergometer test. Steady state protocols were performed at approximately 80% of preflight $\dot{V}O_{2max}$ and interval protocols were performed between 60% and 90% $\dot{V}O_{2max}$ with rest stages varying from 40 to 50% $\dot{V}O_{2max}$. Because there were no preprogrammed TVIS protocols, the crewmember was advised to maintain a heart rate between 75% and 90% of their preflight heart-rate maximum in

Table VII. NASA's Expeditions 20–25 Sample T2 Protocols.

Stage Number	Time (min)	Speed (mph)	Load (lb)
4-MINUTE INTERVAL			
1	4	6	150
2	4	9	150
3	2	6	150
4	4	9	150
5	2	6	150
6	4	9	150
7	2	6	150
8	4	9	150
11	4	6	150
STEADY STATE			
1	3	7.5	150
2	3	7.5	150
3	3	7.5	150
4	3	7.5	150
5	3	7.5	150
6	3	7.5	150
7	3	7.5	150
8	3	7.5	150
9	3	7.5	150
10	3	7.5	150
2-MINUTE INTERVAL			
1	4	6	150
2	2	9	150
3	2	6	150
4	2	11	150
5	2	6	150
6	2	11	150
7	2	6	150
8	2	11	150
9	2	6	150
10	2	11	150
11	2	6	150
12	2	11	150
13	2	6	150
14	2	9	150
15	4	6	150

motorized mode and walk in non-motorized mode at the end of every treadmill session. The external load applied to the crewmember started at 60% body weight and increased as much as tolerable throughout the mission. The crewmember was advised to perform at least one interval protocol per week on both the cycle ergometer and treadmill.

ESA

The ESA countermeasure plan was inspired by the Russian and NASA concepts and further developed using the available scientific literature on human physiology and spaceflight. The ESA plan was an integrated approach, using all exercise equipment available on the ISS. Maintaining an identical PT plan across all ISS ESA astronauts was not possible given the length of time between ESA missions and the difference in exercise hardware available during each mission. Consequently, the ESA countermeasure program has undergone constant modification. The training objective of the in-flight countermeasure program was the preservation of functional strength, muscle and bone mass, and cardiovascular health to maintain in-flight and postflight performance capabilities.

The ESA countermeasure plan constituted an intense daily exercise program using different training modalities and methodologies with crew compliance being one of the most important elements for a successful PT program. Strength training and running were the main focus to maintain gravity-stimulated neuromuscular functionality. The intensity of in-flight PT was designed to be high; with alterations over the week fluctuating between high and low levels. The training was periodized over the entire mission and separated into three phases (**Table IX**): 1) a 2-wk period of low-intensity general exercise to give the astronaut time to adapt to exercising in microgravity; 2) training intensity was increased throughout this period focusing on strength and treadmill training, with some cycle ergometer training; and 3) training intensity was increased for the final 2 to 3 wk, focusing solely on strength and treadmill training to prepare crewmembers for return to Earth.

Strength training loads on iRED and ARED were targeted to be between 60% and 90% of the individual maximal capacity. Lower loads were used in Phase 1 and systematically ramped up every 1 to 2 wk in Phase 2 and 3. Preflight training loads were used to estimate early in-flight resistance; however, given the differences in exercise environments and hardware, they did not always correlate. Critical exercises, such as squats, heel raises, and deadlifts, were prescribed in every training session whereas upper body exercises were more varied. The order of exercises was varied to avoid fatiguing the hands during bar exercises and to allow for the most efficient use of exercise time, rather than for methodological reasons. Squats, heel raises, and deadlift exercises occurred at the beginning of each workout. In preparation for an extravehicular activity, additional exercises were added to the strength training routine to strengthen prime movers (hands, arms, shoulders) and reduce risk for injury. Many crews who trained on iRED reached the maximal load of 136 kg (300 lb) midmission; thus exercise intensity was manipulated by increasing exercise volume (sets and repetitions) rather than load. During ARED exercise, individual exercises and intensities rotated between four different exercise sessions (A, B, C, D) and three different intensity levels (8, 12, or 15 repetitions) (**Table XA** and **Table XB**). This created a systematic shifting of combinations between sessions and intensities that repeated every month. Loads were increased systematically, taking into account crewmember performance and feedback.

Treadmill protocols were created with crewmember participation during the preflight phase. Protocol intensity was increased throughout the mission by modifying running speed and interval duration. Even though some freedom was given to the astronaut, a standard set of protocols was used frequently by the crewmember to monitor his fitness. The treadmill was used in both motorized and nonmotorized modes with an initial external load of at least 60% of the astronaut's body weight and was gradually increased to an average of 70-80% for the duration of the mission. The harness load was increased throughout the mission with the goal of achieving 100% body weight, although no crewmember achieved this goal due to the previously described comfort issues. TVIS protocols were emailed to the astronauts due to technical limitations of the hardware.

Table VIII. NASA's Expeditions 18–25 Sample ARED Exercise Protocols.

A. ARED macro cycle.*

RESISTANCE (% 1 RM)	HEAVY (4 × 6)	LIGHT (4 × 12)	MEDIUM (4 × 8)	HEAVY (4 × 6)	LIGHT (4 × 12)	MEDIUM (4 × 8)
70	1	2	3	2	3	1
75	3	1	2	1	2	3
80	2	3	1	3	1	2
85	1	2	3	2	3	1
90	3	1	2	1	2	3
95	2	3	1	3	1	2
100	1	2	3	2	3	1
105	3	1	2	1	2	3
110	2	3	1	3	1	2
115	1	2	3	2	3	1
120	3	1	2	1	2	3
125	2	3	1	3	1	2

*The numbers 1, 2, and 3 refer to the individual exercise sessions listed in Table VIIIB.

B. Cycle of ARED exercises sessions where each session represents an individual exercise period.

SESSION 1	SESSION 2	SESSION 3
Back Squat	Sumo Squat	Single Leg Squat
Heel Raise	Heel Raise	Sumo Deadlift
Deadlift	Deadlift	Romanian Deadlift
Romanian Deadlift	Shrug	Upright Row
Shoulder Press	Bench	Bicep Curl
Bent-over Row	Tricep Extension	Single Arm Row

When T2 became operational, protocols were directly uploaded to the treadmill.

The NASA Exercise Physiology Laboratory prepared CEVIS exercise protocols with intensities based upon the astronaut's preflight cardiovascular fitness assessment. Training performed on the Russian Velo-ergometer did not require the preparation of protocols because they were available in the onboard documentation. In addition to the monthly fitness assessment on CEVIS, a Russian monthly treadmill protocol (MO-3) was implemented to monitor training progress.

POSTFLIGHT RECONDITIONING

All crewmembers returning from long-duration spaceflight have neurovestibular, orthostatic, back/neck pain, coordination, balance/agility, aerobic, strength, endurance, power, and flexibility issues to some degree and these issues affect each crewmember differently. Following a long-duration mission, each crewmember was scheduled for 2 h of PT everyday (including weekends) for 45 d. The first 10 to 14 d following flight were devoted to PT, medical testing, and data collection for scientific experiments. During this time, crew schedules were limited to 4 h of testing and activities and 2 h of PT. After the first 10 to 14 d, the crew workday returned to normal, 8 h including 2 h of PT. In addition, the crew received a week off from all testing and activities (except for PT) for family reintegration. This week was scheduled any time in the ensuing 2 to 3 wk, depending on postflight activities, crew preference, and medical or experimental testing requirements.

Several factors affected the quality and quantity of postflight PT. Postflight PT sessions did not always last the scheduled 2 h; any events before PT that overran scheduled times caused PT to be shortened due to limitations in the total workday. Time also was lost due to unplanned events that required the astronaut's attention and on many occasions, once a crewmember returned to work PT was shortened, postponed, or removed from the schedule due to activities deemed higher in priority. Fatigue was another factor that impacted PT quality and caused PT sessions to be missed all together. While PT was a contributing factor, over-exertion due to resuming normal activities in a gravitational environment, returning to work, and/or visiting colleagues, friends, and extended family played a role in exacerbating fatigue.

Fig. 1. In-flight exercise of the first JAXA ISS astronaut. CEVIS (left), TVIS (middle), and ARED (right).

NASA

The initial reconditioning program was developed for U.S. astronauts who flew long-duration missions aboard the Russian Mir Space Station. The goal of the reconditioning program was to return each crewmember back to preflight status as quickly and safely as possible. Because the ASCR group had no long-duration spaceflight experience, a very conservative approach was established to prevent injuring the crewmember during reconditioning. During this period, the program consisted of swimming, stretching, elastic band and body weight exercises, and some walking, eventually progressing to light weight training after several weeks. The first 9 ISS expeditions followed the same approach with the exception that weight training started earlier in the program. As the ASCRs became familiar with the performance capabilities of the astronauts returning from ISS, the program evolved over the next nine missions and became more aggressive, adding more complex movements and exercises.

Table IX. ESA's In-Fight Physical Training Plan.*

Session	Exercise Hardware	Time	Exercise Hardware	Time
PHASE 1				
1	TM	60	CEVIS	60
2	CEVIS	60	RED	90
3	TM	60	CEVIS	60
4	CEVIS	60	RED	90
5	TM	60	CEVIS	60
6	TM	60	RED	90
7	CEVIS	60	RED	90
PHASE 2				
1	RED	90	TM	60
2	RED	90	CEVIS	60
3	RED	90	TM	60
4	RED	90	CEVIS	60
5	RED	90	TM	60
6	RED	90	CEVIS	60
7	RED	90	TM	60
PHASE 3				
1	RED	90	TM	60
2	RED	90	TM	60
3	RED	90	TM	60
4	RED	90	TM	60
5	RED	90	TM	60
6	RED	90	TM	60
7	RED	90	TM	60

* Each session is an individual exercise period and the 7 sessions listed repeat for the duration of each phase. RED refers to resistive exercise and TM refers to treadmill exercise.

Since the implementation of more capable exercise hardware aboard the ISS, the reconditioning program became even more aggressive to decrease the recovery time of a better-conditioned returning crew (**Table XI**). Following their return, each astronaut performed some form of aerobic exercise, dynamic stretching and warm-up, core exercises, and static stretching every day. Each of these activities increased in difficulty as the crewmember's physical capacity increased. For example, aerobic exercise was conducted initially on a recumbent cycle to focus on aerobic conditioning and prevent neurovestibular issues from impacting the exercise. The crewmember then proceeded to upright exercise on an elliptical trainer, followed by a treadmill, and finally outdoor running. In addition, each crewmember performed resistance exercise and general performance skills on alternating days. The resistance exercise routine consisted of the same exercises performed during their flight with increasing loads throughout the reconditioning period. The general performance skills consisted of power, agility, balance, and coordination drills that increased in difficulty as the crewmember improved.

JAXA

The goal of the postflight reconditioning program was to provide a planned and supervised program of recovery that would prevent injury, provide progressive improvement in fitness and health parameters, assist in a rapid return to functional status, and enable a full return to preflight baseline levels. The Japanese astronauts followed the NASA postflight reconditioning protocol (**Fig. 2**), as described previously, and progression through the program was based on the crewmember's physical condition and postflight medical data.

CSA

The objective of postflight PT was to assist crewmembers in safely returning to their preflight levels of physical fitness. The CSA reconditioning program was based on the NASA postflight reconditioning protocol, as described previously, and included exercises for flexibility, balance, agility, coordination, muscular strength and endurance, and cardiorespiratory fitness. Progression through the program was based on the crewmember's physical condition and postflight medical data.

ESA

As with the other International Partners, the prime objective during postflight reconditioning was to return the astronaut to preflight physical performance levels. Postflight reconditioning was conducted by the ESA team and jointly planned with and implemented in the host country (U.S. or Russia). The reconditioning plan was split into two phases: Phase 1, the acute phase, was performed 2 h • d^{-1} between R+1 and R+21 and Phase 2, which was performed between R+21 and R+45 with reduced supervision. During Phase 1, the intensity level increased progressively without evoking strong physical fatigue effects, but still stimulated readaptation to a gravitational environment. One day of rest usually was given following the first 2 wk of reconditioning. During Phase 2, the crewmember was given an individual training program similar to the preflight exercise routine with the goal of returning to preflight levels of physical activity.

Table X. ESA's ARED Exercise Protocol.

A. ESA's ARED 4-Week Cycle.*

WEEK	15 REPS	12 REPS	8 REPS	15 REPS	12 REPS	8 REPS	15 REPS
1	A	B	C	D	A	B	C
2	D	A	B	C	D	A	B
3	C	D	A	B	C	D	A
4	B	C	D	A	B	C	D

*The Letters A, B, C, and D refer to the individual exercise sessions listed in Table XB.

B. ESA's ARED Exercise Sessions Where Each Session Represents an Individual Exercise Period.

SESSION A	SESSION B	SESSION C	SESSION D
Squat	Single Leg Squat	Squat	Single Leg Squat
Single Leg Heel Raise	Heel Raise	Single Leg Heel Raise	Heel Raise
Deadlift	Romanian Deadlift	Deadlift	Romanian Deadlift
Shoulder Press	Upright Row	Bench Press	Upright Row
Bent-over Row	Tricep Extension	Shoulder Shrug	Bicep Curl
Crunches	Crunches	Crunches	Crunches

Table XI. Overview of the NASA Postflight Reconditioning Program.*

SECTION	TITLE	PRIMARY BENEFIT	SECONDARY BENEFIT	SCHEDULE
1	Dynamic stretch and warm-up	Warm-up and flexibility	Balance, coordination, orthostasis, and vestibular	Every day R+1 thru R+45
2	Aerobic conditioning	Cardiovascular conditioning	Orthostasis	Every day: R+1 thru R+45
3	Resistance exercise	Muscular strength and endurance	Balance, coordination, orthostasis and vestibular	Every other day R+1 thru R+45
4	Mobility, balance and proprioception drills	Mobility, coordination, balance, proprioception, and vestibular	Muscular strength and endurance and orthostasis	Every other day R+1 thru R+45
5	Medicine ball drills	Muscular power	Muscle strength and endurance, coordination, balance, and vestibular	Every other day R+1 thru R+45
6	Cone and agility ladder drills	Multiplanar mobility, agility, coordination and balance	Vestibular conditioning	Every other day R+6 thru R+45
7	Jumping drills	Multiplanar power, agility, coordination and balance	Vestibular conditioning	Every other day R+21 thru R+45
8	Core exercise	Abdominal and low back strength and endurance	Vestibular conditioning	Every day R+1 t R+45
9	Static stretching	Flexibility		Every day R+1 thru R+45

* R+ refers to the number of days since the astronauts returned to Earth. (Reprint from Wood et al. 2011).[4]

The reconditioning program started with basic movements and built upon itself to eventually return each astronaut to preflight performance levels. Reactivation of the stabilizer muscles and an intensive neurophysiological training regimen were the first elements targeted to create a stable base for the subsequent training interventions. Starting at R+3, core stabilization exercises were completed in the pool for the first 2 wk using the buoyancy effects of the water to provide a safe environment to perform neuromuscular, local muscular endurance, and cardiovascular training. Training intensity and complexity were progressively increased with each session, leading to gym-based training activities consisting of resistance, agility, balance/coordination, velocity, and flexibility training to develop full functionality and return to activities of daily living. Physical conditioning was continued in the weeks and months after the formal postflight period ended by means of an individual training program.

SUMMARY

There is still much to learn before we fully understand the impact of current flight hardware and exercise prescriptions on in-flight and postflight human physical performance. Our present results indicate that as exercise hardware and prescription capabilities have improved, so has postflight physical performance.[4] Going forward, there are several changes that may enhance the effectiveness of PT. Given the different training environments (gravity vs. microgravity) and hardware, it is difficult to predict appropriate exercise loads for use in microgravity. Understanding the correlation between preflight and in-flight loading might minimize the immediate effects of spaceflight and help to optimize exercise prescriptions. While there are many postflight tests to monitor performance changes following spaceflight, the CEVIS fitness assessment is the only in-flight test to monitor performance over time. Understanding performance changes should enhance the efficacy of the in-flight exercise prescription and postflight reconditioning protocol. Finally, in-flight treadmill exercise is poorly understood, which makes it difficult to determine an effective prescription. A full understanding of the relationship between heart rate, belt speed, and subject loading would allow the practitioner to prescribe more effective treadmill exercise in microgravity.

Exercise programs affect multiple physiological systems and, given the various constraints and limited exercise time during all three phases of a mission, it is important to maximize the effectiveness of the exercise program. In addition, it must be recognized that while an exercise program has been prepared to cover all three phases of a mission, a high degree of flexibility is necessary to account for real-time changes and the various constraints that occur during each phase of training. While these factors do not preclude exercise programs from being similar, agency specific philosophical differences in exercise prescription do affect the methodologies used to achieve astronaut health. Therefore when evaluating physiological data collected during a mission, it is important to understand which agency was responsible for PT, the nature and composition of the subject population, and any limitations such as hardware failures that may have affected the data quality. As we plan exploration missions, these differences will continue until the international space community

Fig. 2. Readaptation training of the first JAXA ISS astronaut using medicine ball, rubber band exercises, balance exercises, and body weight exercises.

can establish a minimum set of fitness and performance standards for human spaceflight.

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