The First Decade of ISS Exercise: Lessons Learned on Expeditions 1–25

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INTRODUCTION: Long-duration spaceflight results in musculoskeletal, cardiorespiratory, and sensorimotor deconditioning. Historically, exercise has been used as a countermeasure to mitigate these deleterious effects that occur as a consequence of microgravity exposures. The International Space Station (ISS) exercise community describes their approaches, biomedical surveillance, and lessons learned in the development of exercise countermeasure modalities and prescriptions for maintaining health and performance among station crews. This report is focused on the first 10 yr of ISS defined as Expeditions 1–25 and includes only crewmembers with missions > 30 d on ISS for all 5 partner agencies (United States, Russia, Europe, Japan, and Canada). All 72 cosmonauts and astronauts participated in the ISS exercise countermeasures program. This Supplement presents a series of papers that provide an overview of the first decade of ISS exercise from a multidisciplinary, multinational perspective to evaluate the initial countermeasure program and record its operational limitations and challenges. In addition, we provide results from standardized medical evaluations before, during, and after each mission. Information presented in this context is intended to describe baseline conditions of the ISS exercise program. This paper offers an introduction to the subsequent series of manuscripts.

KEYWORDS: exercise countermeasures, treadmill, resistance exercise, ergometer, prescription.

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It is well established that living in a microgravity environment results in deconditioning effects on the musculoskeletal, neurosensory, cardiovascular, and respiratory systems that may impair crew health and performance.[2,4–7] This is important as astronaut and cosmonaut fitness affects safety and the success of their occupational tasks in space.[1]

Maintaining a healthy and fit crew on board the International Space Station (ISS) has been an evolutionary process.[8] The operational realities of exercising on the ISS evolved through decades of development, international negotiations on functional system requirements, lessons learned, cultural understanding, evidence-based analyses of related research, and resource limitations. The Life in Space for Life on Earth meeting, held in Trieste, Italy, provided the opportunity for representatives from ISS partner agencies to hold a satellite workshop to specifically share their operational approaches and findings related to exercise countermeasures and medical outcomes.

The principal objective of this supplement is to document the operational ISS exercise countermeasures system and the associated health outcomes of astronauts and cosmonauts during Expeditions 1–25, the first 10 yr of ISS. This *Aerospace Medicine and Human Performance* journal supplement describes events, records lessons learned, and assesses biomedical results obtained during the first decade of ISS. Considerable knowledge has been gained, but clearly much has yet to be fully understood. The ISS exercise challenges may seem trivial to those unfamiliar with the processes; however, the result has been a noteworthy journey that involved scientists, physicians, and engineers from around the globe. This collaboration involved representatives from the space exercise countermeasures communities of the ISS International Partners (IPs), specifically the Institute of Biomedical Problems (IBMP) of the Russian Academy of Sciences and the members of the U.S. Operations Segment (USOS): Japan Aerospace Exploration

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Agency (JAXA), Canadian Space Agency (CSA), European Space Agency (ESA), and NASA.

The process was initiated by a thorough review of historical evidence from Skylab, Mir, and Space Shuttle, as well as terrestrial evidence from focused analog studies using bed rest and dry immersion.[3,5,6,8] The specialists worked collaboratively to establish exercise strategies that would maintain crew health and performance during and after ISS missions. Multiple and sometimes conflicting considerations for managing crew performance included mission duration, occupational tasks, and resource management (i.e., crew time, station power and volume, upmass, etc.).

Biomedical scientists seek basic information on exercise in space and how it affects their research because to date this information has not been published. This Supplement provides a full description of pre-, in-, and postflight countermeasure systems and their implementation. It provides a compendium of exercise system data for researchers and clinicians to draw from as they interpret their results and/or plan for future human research on ISS.

This series of papers is intended to describe the operational realities of exercise countermeasures and to characterize the performance outcomes from the first decade of ISS. It provides: an introduction to the ISS exercise countermeasures system; descriptions of ISS exercise modalities and lessons learned while employing them; pre-, in-, and postflight exercise prescriptions; specific outcomes in the areas of musculoskeletal, neurosensory, and cardiovascular fitness based upon results from required standardized medical assessments tests; and a summary of our international experience and vision for the future of utilizing exercise countermeasures for exploration class missions.

The information and data have been collected systematically as part of normal operations – these data were not part of any research study. The data include analyses of non-attributable medical data for every ISS crewmember. A substantial effort was required to compile this information in compliance with multinational agreements. This Supplement includes the following papers that were submitted with the cooperation of the ISS IPs:

- Exercise Countermeasure Hardware Evolution on ISS: The First Decade
- Physical Training for Long-Duration Spaceflight
- Russian Countermeasure Systems for Adverse Effects of Microgravity on Long-Duration ISS Flights
- Evolution of Russian Microgravity Countermeasures
- Evaluating Bone Loss in ISS Astronauts
- Assessing Sensorimotor Function Following ISS with Computerized Dynamic Posturography
- Orthostatic Intolerance after ISS and Space Shuttle Missions
- Isokinetic Strength Changes Following Long–Duration Spaceflight on the ISS
- The First 10 Years of Aerobic Exercise Responses to Long-Duration ISS Flights
- Functional Fitness Testing Results Following Long-Duration ISS Missions

Table I. USOS Medical Assessment Tests Associated with Exercise Outcomes.

REQUIREMENT	DESCRIPTION
Operational Tilt Test	A standardized measure of orthostatic stability as measured by heart rate and blood pressure during a tilt-table test
Bone Densitometry	A measure of bone mineral density using a dual energy x-ray absorptiometry (DXA) for assessing the whole body, lumbar spine, femoral neck, calcaneus and forearm
Neurovestibular Platform Test	A functional assessment of neurovestibular balance control and sensory integration as measure by the Equitest posture platform and motion analysis
Cycle Ergometer Test/Aerobic Functional Capacity	A graded exercise test using a cycle ergometer to assess aerobic capacity ($V\text{O}_2$) and heart rate
Functional Fitness Assessments	A series of field tests designed to assess fitness as determined by flexibility, strength, endurance, power, sensorimotor integration/agility and balance
On-Orbit Strength & Conditioning Monitoring	Fitness monitoring of each crewmember's performance during space missions
Isokinetic Testing	An objective measure of isokinetic strength and endurance of the muscles surrounding the ankle, knee, and torso
Heart Rate Monitoring	Heart rate monitoring during aerobic exercise
Postflight Rehabilitation	Reconditioning activities of astronauts and cosmonauts following ISS missions.

- Exercise Countermeasures on ISS: Summary and Future Directions

Each paper describes the approach and/or results in a specific realm of the overall ISS exercise countermeasures effort. While each paper can stand alone on its own merit, in reality the effort was not so autonomous and this multinational endeavor is deliberately woven together such that each paper forms a part that complements the others. Hence, the Supplement. It is important to read the full series to obtain a comprehensive historical perspective of the evolution of the ISS countermeasures.

Table II. Summary of Russian Measures.

REQUIREMENT	DESCRIPTION
Treadmill Locomotor Test	A graded exercise test with increasing workloads over time on a treadmill
Cycle Ergometer Test	A graded exercise test with increasing workloads over time on a cycle ergometer
Hand Ergometer Test	A pre-extravehicular activity fitness test using constant load during arm ergometry
Muscle properties	Isokinetic dynamometry, tetanic contractions, and muscle biopsy
Motor Control	Tests of tendon reflex, equilibrium, strength, head and eye coordination and locomotion
Osteodensitometry	A measure of bone mineral density
Vestibular system tests	Battery of sensory adaptation

METHODS

The NASA Lifetime Surveillance of Astronaut Health committee has approved the release of crew medical data presented in these manuscripts as population-based analyses of astronaut outcomes related to exercise countermeasure effectiveness. All assessments involved retrospective data mining and individual data were non-attributable thereby concealing crewmember identity and protecting their medical privacy. These data were compiled from the standardized medical assessment tests performed before, during, and after ISS space missions (**Table I**). Similarly, the Institute of Biomedical Problems (IBMP) specialists have compiled data from their studies to provide outcomes of their countermeasures program that supports cosmonauts (**Table II**). The results include data obtained from ISS Expeditions 1–25. These tests collected data per the requirements outlined by NASA documents (JSC 24,834 – Astronaut Medical Evaluation Requirements Document [AMERD], JSC 28,913 Rev. A – Medical Requirements Integration Documents [MRIDS], SSP 50,260 Rev. C – ISS Medical Operations Requirements Document [MORD], and SSP 50,567 – Medical Evaluation Requirements for Long Duration ISS Crewmembers).

Cosmonaut reports were compiled, analyzed, and interpreted by the IBMP specialists while the USOS astronaut results were assembled by NASA experts in cooperation with USOS partners (JAXA, CSA, and ESA).

During the first decade of ISS, the increment durations generally increased up to 6 mo over time and remained at a crew size of three with a few exceptions after the Columbia accident (**Table III**). The cohort in these papers focus on those crewmembers whose missions exceeded 30 d in duration. Thus there were 72 crewmember exposures ranging from 48 to 215 d ($\mu = 169.3, \sigma = \pm 31.8$). This equates to 12,188 person-days in space for the first 25 missions.

In this timeframe, there were eight female astronaut assignments, all from NASA; one flew on two expeditions. Repeat fliers, assigned to two different missions, hail only from the U.S. and Russia, totaling three and seven crewmembers, respectively. The average age at landing for the entire cohort was approximately 46.2 yr. The distribution of crewmembers per agency follows in **Table IV**.

Table III. ISS Crewmembers and Mission Duration.

EXP	CREWMEMBER	SPACE AGENCY	DURATION (DAYS)	EXP	CREWMEMBER	SPACE AGENCY	DURATION (DAYS)
1	Yuri Gidzenko	Russia	141	15	Oleg Kotov	Russia	197
1	Sergei Krikalev	Russia	141	15	Fyodor Yurchikhin	Russia	197
1	William Shepherd	US	141	15/16	Clayton Anderson	US	152
2	Yury Usachev	Russia	167	16	Leopold Eyharts	ESA	48
2	Susan Helms	US	167	16	Yuri Malenchenko	Russia	192
2	James Voss	US	167	16	Peggy Whitson	US	192
3	Vladimir Dezhurov	Russia	129	16	Daniel Tani	US	120
3	Mikhail Tyurin	Russia	129	16/17	Garrett Reisman	US	95
3	Frank Culbertson	US	129	17	Sergey Volkov	Russia	199
4	Yuri Onufrienko	Russia	196	17	Oleg Kononenko	Russia	199
4	Daniel Bursch	US	196	17/18	Gregory Chamitoff	US	183
4	Carl E. Walz	US	196	18/19/20	Koichi Wakata	JAXA	138
5	Sergei Treschev	Russia	185	18	Yuri Lonchakov	Russia	178
5	Valeri Korzun	Russia	185	18	Michael Fincke	US	178
5	Peggy Whitson	US	185	18	Sandra Magnus	US	134
6	Nikolai Budarin	Russia	161	19/20	Michael Barratt	US	199
6	Kenneth D. Bowersox	US	161	19/20	Gennady Padalka	Russia	199
6	Donald Pettit	US	161	20/21	Frank De Winne	ESA	188
7	Yuri Malenchenko	Russia	185	20/21	Roman Romanenko	Russia	188
7	Edward Lu	US	185	20	Timothy Kopra	US	58
8	Alexander Kaleri	Russia	195	21	Robert Thirsk	CSA	188
8	Michael Foale	US	195	21	Nicole Stott	US	91
9	Gennady Padalka	Russia	186	21/22	Jeffrey Williams	US	169
9	Michael Fincke	US	186	21/22	Maxim Suraev	Russia	169
10	Salizhan Sharipov	Russia	192	22/23	Soichi Noguchi	JAXA	163
10	Leroy Chiao	US	192	22/23	Timothy (T.J.) Creamer	US	163
11	Sergei Krikalev	Russia	179	22/23	Oleg Kotov	Russia	163
11	John Phillips	US	179	23/24	Tracy Dyson	US	176
12	Valery Tokarev	Russia	189	23/24	Alexander Skvortsov	Russia	176
12	William McArthur	US	189	24	Mikhail Kornienko	Russia	176
13/14	Thomas Reiter	ESA	171	24/25	Shannon Walker	US	163
13	Pavel Vinogradov	Russia	183	24/25	Douglas Wheelock	US	163
13	Jeffrey Williams	US	183	24/25	Fyodor Yurchikhin	Russia	163
14	Mikhail Tyurin	Russia	215	25/26	Scott Kelly	US	160
14	Michael Lopez-Alegria	US	215	25/26	Alexander Kaleri	Russia	160
14/15	Sunita Williams	US	195	25/26	Oleg Skripochka	Russia	160

Table IV. Agency Crewmember Distribution.

AGENCY	CREW ASSIGNMENTS	PERSON-DAYS	REPEAT FLIERS	FEMALE ASSIGNMENTS	AVERAGE AGE
CSA	1	188	0	0	56
ESA	3	407	0	0	49
JAXA	2	301	0	0	45.5
Russia	32	5674	7	0	43.7
NASA	34	5618	3	8	46.7
Totals	**72**	**12,188**	**10**	**7***	**46.2**

* One female astronaut flew on two assignments.

The ISS crews are assigned approximately a year in advance of the mission and spend much of their time training together at each of the partner agencies. They were strongly encouraged to exercise preflight in preparation for their upcoming mission and time was scheduled for this activity regardless of where their duty station was located across the globe.

It is important to note that the ISS was under construction during this first decade and its capabilities, including exercise countermeasures, gradually improved over the course of each increment (**Fig. 1**). Operational exercise countermeasure systems were provided by the NASA and Russian programs. The vehicle configuration and enhancements were modified during the ISS assembly phase with every Soyuz and Space Shuttle mission. Correspondingly, exercise countermeasure systems and associated monitoring hardware evolved over ISS increments, slowly increasing the on-board capabilities. As outlined in the shared requirements documents agreed to by all ISS partners, astronauts and cosmonauts were allotted 2.5 h per day during the mission for exercise countermeasures that included cardiovascular and resistance exercise. In addition to exercise, this time accommodated equipment set-up and reconfiguration as well as cool down and personal hygiene activities.

Systems were launched over the progression of ISS assembly. Russian hardware typically was housed in the Russian segments, while the NASA systems were integrated into the USOS segments, with the exception of the TVIS treadmill that was located in the Russian Zvezda Service Module until it was decommissioned during Expeditions 21–22. While the countermeasure equipment was moved during the early evolution of ISS, **Fig. 2** depicts the original set of hardware and with on-orbit locations distributed throughout the station.

It is critical to note that, in spite of the inter-Agency commitment to in-flight exercise and common requirements across the IPs, the condition of ISS crewmembers varied greatly. The approaches to postflight rehabilitation and recovery phases were managed by their respective physicians and trainers. Every crewmember was provided daily reconditioning activities that were scheduled throughout the first 45 d after landing to prepare them for terrestrial living and return them to their preflight baseline wherever possible.

The data presented in this supplement show that even with an in-flight exercise program, we still observed losses in skeletal muscle strength and endurance, aerobic capacity, bone health, and postural stability. Therefore our collective experience gained through ISS Expedition 25 has shown that exercise countermeasures have been only partially successful in mitigating deconditioning. This series of manuscripts details the obstacles encountered while developing and sustaining reliable exercise systems in a resource-constrained space environment.[3] The "lessons learned" here about exercise countermeasures define the multiple factors that contribute to the health and performance outcomes of each crewmember: dependability of the systems, the preflight limitations on the crew for physical conditioning, on-orbit crew time impacts, and the ability to accommodate varied, tailored therapeutic intervention doses necessary to sustain fitness among the full distribution of crewmembers across the population from the 5th to 95th percentile body dimensions. It is important to note that although the USOS and Russian approaches to exercise in space have both similarities and differences in both their tactics and priorities; the ISS crews are intermingled and required to function as a cohesive team throughout their training and flight (**Fig. 3**). While the general prescription methodology varies by agency,

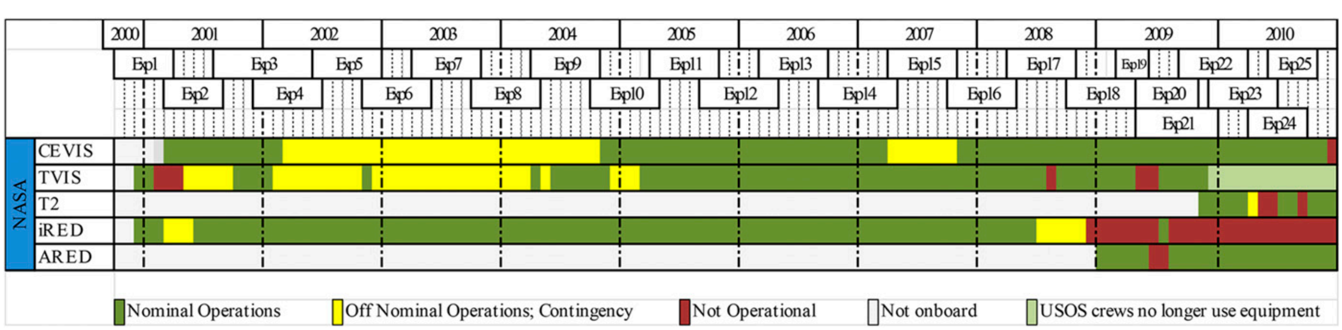

Fig. 1. ISS Exercise Countermeasures Evolution Timeline. This timeline identifies the missions and functionality of various exercise countermeasures equipment during operations. The timeline depicts when countermeasures were fully functional, off nominal, not operational, unused, or not yet onboard. The NASA countermeasures include: cycle ergometer with vibration isolation and stabilization (CEVIS), treadmill with vibration isolation (TVIS), interim resistive exercise device (IRED), and advanced resistive exercise device (ARED). This illustration does not show the Russian hardware timeline. All exercise systems are fully described within the Supplement in their respective papers.

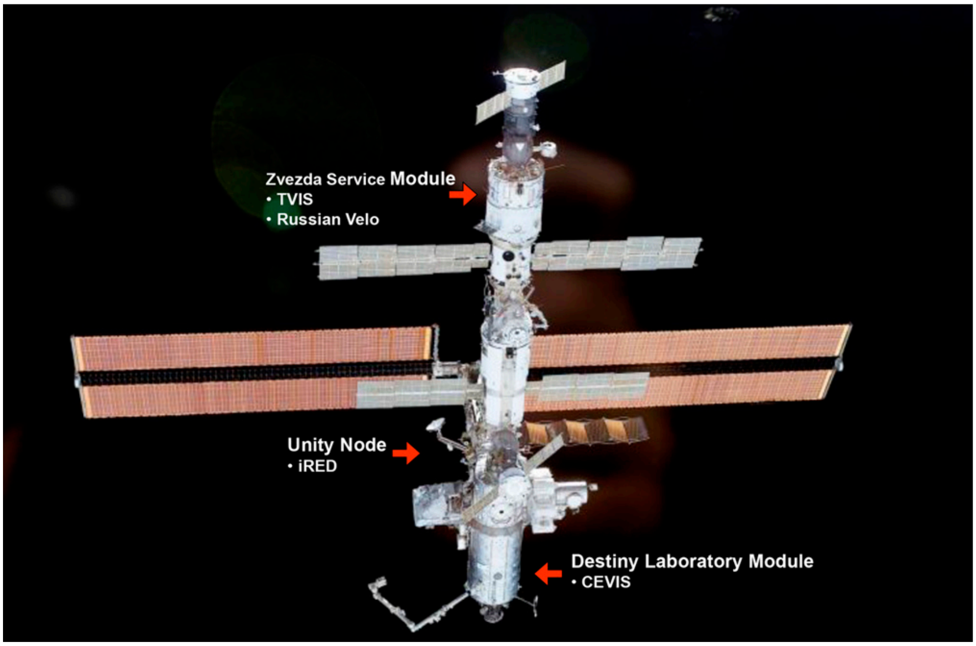

Fig. 2. Early ISS exercise countermeasures hardware locations.

all agency representatives share the common goal of maintaining crew health, safety and performance. This occasionally required crossover or system resource sharing in times of need (i.e., when specific systems were deemed temporarily inoperable) to maintain uninterrupted countermeasures support to all crewmembers throughout each expedition. This Supplement documents the methodologies and shares the respective outcomes.

CONCLUSIONS

This effort was initiated following the Life in Space for Life on Earth workshop to communicate information with the greater community and to provide a historical perspective of what is known about the ISS exercise systems and resulting performance outcomes of its earliest crews. Meeting the challenges that accompanied the progression of exercise systems from the beginning of the ISS has energized the global exercise community in preparation for the next phases of human space exploration. The ISS has been and continues to be a valuable research platform for evaluating new prescriptions and technologies as we venture into areas of prescription optimization, virtual coaching, autonomous recovery rehabilitation, system reliability, and miniaturization. Development of effective systems can be laden with difficult requirements, systems development challenges, complex negotiations or barters, and research. This Supplement provides a baseline record of "lessons learned" and a catalyst for leveraging further international efforts to optimize exercise systems for longer ISS expeditions as well as missions that might return humans to the Moon or an asteroid, and eventually to Mars.

Fig. 3. Preflight exercise on the grounds of the Cosmonaut Hotel, Baikonur, Kazakhstan: Expedition 9 crewmembers Russian cosmonaut Commander Gennady I. Padalka (center) and NASA astronaut Mike Fincke (right) train with ESA Soyuz astronaut Andre Kuipers (left). JSC2004-E-20,746 (16 April 2004).

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REFERENCES

1. Ball JR, Evans SH,editors Safe passage: astronaut care for exploration. Washington (DC):Institute of Medicine, National Academy Press; 2001.
2. Buckey JC. Space physiology. New York (NY): Oxford Press; 2006.
3. Davis SA, Davis BL. Exercise equipment used in microgravity: challenges and opportunities. Curr Sports Med Rep. 2012; 11(3): 142–7.
4. Hayes JC. The 'why' and 'how' of exercise on the Space Shuttle. In: Hale W, Lane HW, Lulla K, Chapline G, editors. Wings in orbit: scientific and engineering legacies of the Space Shuttle: 1971-2010. Washington (DC): US Government Printing Office, NASA/SP; 2011.

5. Hayes JC, Guilliams ME, Lee SMC, MacNeill KB, Moore AD. Exercise: developing countermeasures systems for optimizing astronaut performance in space. In: Risin D, Stepaniak PC, editors. Biomedical results of the Space Shuttle Program. Washington (DC): US Government Printing Office, NASA/SP; 2013:289-314.
6. Michel EL, Johnston RS, Dietlein LF (eds.). Biomedical results of the Skylab program. Life Sci Space Res. 1976; 14:3–18.
7. Osborn MJ. Committee Chairperson. National Academy of Sciences. National Research Council Committee on Space Biology and Medicine. A Strategy for Research in Space Biology and Medicine in the New Century. Washington (DC): National Academy Press; 1998.
8. Sawin CF, Hayes JC, Francisco DF, House N. Considerations for development of countermeasures for physiological decrements associated with long-duration human space missions. Acta Astronaut. 2007; 60(4-7):488–496.