One-Year Mission on ISS Is a Step Towards Interplanetary Missions

Elena V. Fomina; Nataliya Yu. Lysova; Tatyana B. Kukoba; Alexey P. Grishin; Mikhail B. Kornienko

BACKGROUND: in the 1990s Russian cosmonauts performed six long-duration missions on Mir that went from 312 to 438 d. In 2015 a mission on the International Space Station that continued for 340 d, 8 h, and 47 min was successfully accomplished. It was a joint U.S./Russian mission completed by Scott Kelly and Mikhail Kornienko (KM).

METHODS: The intensity of in-flight physical exercises and postflight motor changes were measured in KM and in the six cosmonauts who made shorter flights (173.3 ± 13.8 d) on ISS while using similar countermeasures against the adverse effects of microgravity.

RESULTS: It was found that both parameters varied similarly in spite of the difference in the duration of ISS missions. KM maintained adequate physical performance throughout the entire flight; moreover, the level of postflight changes he displayed was comparable to that recorded in the group of cosmonauts who completed 6-mo missions on ISS.

DISCUSSION: In summary, the 1-yr mission has clearly demonstrated the high efficacy of the countermeasures used by KM.

KEYWORDS: physical exercise, microgravity, muscle force-velocity characteristics, electromyography, countermeasures.

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On Earth the cardiovascular,[22] respiratory,[1] and motor systems[12] are primarily responsible for adequate physical performance,[2,20] while in space these very systems develop both structural and functional changes[13,19,21] which may impact human performance (the functional capabilities of crewmembers). Physical exercises are used in microgravity as the major method for maintaining high performance,[15,16] maximum oxygen consumption,[18] proprioception, muscle[6,7,24] and bone functions,[3] motor control,[11] and orthostatic tolerance.[4] Although scientists responsible for medical support in long-duration space missions are still developing and validating methods and combinations of methods that may help maintain cardiovascular and motor functions at the preflight level,[3,6] physiological mechanisms underlying performance changes in microgravity remain insufficiently understood.

Since 1961, when Yuri Gagarin made his first-man-in-space flight of 108 min, the duration of space missions has increased incrementally. The following Russian cosmonauts performed six long-duration missions on Mir: Yuri Romanenko—326 d; Vladimir Titov and Musa Manarov—365 d; Sergey Krikalev—312 d; Valery Polyakov—438 d (which still remains the longest space mission); and Sergey Avdeev—379 d.

Until recently, the duration of the longest mission on the ISS was 213 d. However, in 2014 the decision was made to resume very-long-duration missions, and in 2015 a mission that continued for 340 d, 8 h, and 47 min was successfully accomplished. It was a joint U.S./Russian mission completed by Scott Kelly and Mikhail Kornienko (KM). The duration of regular missions is about half a year. The mission duration of 340 d is very long, though much shorter than that of interplanetary missions that may continue for 3 yr. The 1-yr mission was viewed as a step toward future exploration missions, which was needed to identify the acceptable range of homeostatic changes as well as to discriminate between adaptation and pathology. For obvious reasons, successful implementation of an interplanetary mission will be largely determined by crew health and

From the Institute of Biomedical Problems, Russian Academy of Sciences, Moscow, Russia.

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Address correspondence to: Elena V. Fomina, Laboratory of Countermeasures to Negative Effects of Microgravity, Institute of Biomedical Problems RAS, Moscow, Russia; fomin-fomin@yandex.ru.

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performance. In view of this, it is highly important to use orbital flights on ISS as an opportunity to elucidate human physiological functions in microgravity. At present scientists are actively involved in the development of means and methods for controlling adaptive changes that occur during extended exposure to the space environment as well as effective countermeasures that can offset adverse effects of the exposure and maintain the physical capabilities of crewmembers at the level that will allow them to work efficiently on the surface of another planet.[5,7,9] The purpose of the present investigation was to compare the in-flight exercise intensity and postflight physiological changes shown by the cosmonaut from the 1-yr mission and the cosmonauts from 6-mo missions.

METHODS

The effectiveness of countermeasures in long-duration missions was measured through comparison of exercise intensity and motor changes shown by the cosmonaut from the 1-yr mission and the six crewmembers from shorter missions (173.3 ± 13.8 d), which were viewed as controls. All these crewmembers used a similar program of countermeasures against the adverse effects of microgravity.

The Russian program consists of exercises performed twice a day for a total of 150 min daily. Every day the crewmembers were recommended to use a treadmill (BD-2) and a cycle ergometer, alternating Russian (VB-3M) and U.S. (CEVIS) devices, as well as the Advanced Resistive Exercise Device (ARED). **Table I** illustrates a typical microcycle of the Russian training protocol.

Earlier we compared the two groups of cosmonauts who used different modes of locomotor exercise: interval training in the aerobic-anaerobic power zone and continuous low-intensity training in the aerobic power zone of energy supply for muscle activity. Interval training with multiple transitions between aerobic and anaerobic mechanisms of energy for muscle activity makes it possible to maintain performance capacity during a prolonged exposure to microgravity. The in-flight performance levels were not different from the preflight values, as evidenced by the ergonomic, metabolic, and physiological characteristics of the work during locomotor tests with a stepwise increasing load.[9]

Locomotor exercise was actually running and walking on a treadmill 2–4 times within a 4-d microcycle. Heart rate averaged 140–160 bpm, reaching a maximum of 180 bpm. Each training period started with passive locomotion and included two intervals of walking and running.

On Day 1, an exercise session included four intervals of fast running at a speed of 14 km/h for 1 min, each interrupted by walking for 2 min. On Day 2, an exercise session included three intervals of running arranged as two passive intervals at a speed of 8 km/h and one active interval at a speed of 12 km/h for 2 min, interrupted by 2-min walking intervals. On Day 3, an exercise session included two intervals of running at a speed of 12 km/h for 4 min. This regimen facilitated the development of endurance[10] that stabilized oxygen uptake and improved blood supply to tissues/organs.[20] On Day 4, the crewmembers were allowed to have rest or exercise according to their personal protocol.[9] The crewmembers were advised 30–40 d prior to the landing to perform locomotor exercise two times a day, with the second microcycle identical to the one done on Day 1; according to our observations, this regimen increased orthostatic tolerance and vascular tonicity.[10]

Resistive exercises were carried out every other day or 3–4 times a week. They included leg muscle exercise (i.e., squat and heel raises) plus shoulder muscle exercise (i.e., shrugs, bench press, cable tricep extension, cable upright row, cable bicep curl) as part of one regimen and torso muscle exercise as part of the other regimen (crunches, deadlift, Romanian dead lift). The exercise prescription called for each specific exercise to be repeated 3–4 times. Recommended squat load was 70–90% bodyweight, while recommended heel raising load was 90–110% bodyweight. A minimum of 30 repetitions was prescribed for each movement.

In the 1-yr mission on ISS, the cosmonaut's performance was monitored on a regular basis. Performance of locomotor exercise was monitored using weekly downloads of the treadmill data, like in a regular spaceflight. Based on the data, physical endurance was assessed; corrections, if needed, were formulated and uplinked by the flight surgeon. The following parameters of locomotor training were evaluated: duration, speed in the range of 4 to 20 km/h, weight loading, treadmill belt mode (BD-2 allows two modes of operation, viz., active, i.e., motor-driven, and passive, i.e., leg-driven), and heart rate (HR).

Physical endurance and resistive exercise performed by the crew using ARED were evaluated with the help of tables that each crewmember was to fill out after an exercise session. Reps, set, and load were included in the tables. Based on the downlinked data, exercise efficacy was assessed and appropriate recommendations were delivered to the crewmembers.

In space, physical endurance of the crew and the efficacy of countermeasures were measured by means of a standard treadmill-based loading (fitness) test designated as MO-3, which was performed about once a month. The test was carried out when the BD-2 functioned in a passive mode and included the following five steps: 3 min of warm-up walk, 3 min of slow running, 3 min of running at a moderate speed, 1 min of running at a maximum speed, and 3 min of cooling-down walk. On

Table I. Microcycle of the Russian In-Flight Training Protocol.

	TRAINING DAY AND EXERCISE DURATION			
COUNTERMEASURE	**DAY 1**	**DAY 2**	**DAY 3**	**DAY 4**
Treadmill BD-2	90 min	90 min	90 min	0–90 min
ARED		60 min		60 min
VB-3M/CEVIS	60 min		60 min	

ARED: advanced resistive exercise device; VB-3M: Russian cycle ergometer; CEVIS: U.S. cycle ergometer.

the whole, the test took 11 min and its caloric value was approximately 100 kcal. The sequence and duration of the steps are preprogrammed and the workload (speed) can be chosen individually. HR, speed, and load levels are the key parameters used for analysis. Performance capacity was assessed in relation to the physiological cost of work (physiological cost index) calculated as a ratio of heart rate (bpm) to the running speed at a maximum speed step (km/h) and load levels (% of bodyweight):

$$PhC = \frac{\Delta HR}{V \times Load} \qquad \text{Eq.1}$$

Where PhC = physiological cost, ΔHR = HR fast running − HR rest, V = speed, and Load = axial load.

Preliminary experiments showed that the speed levels selected by the crewmembers were important indicators of their conditioning. This test is a standard that determines physical strength and endurance of crewmembers used in the Russian medical support system. It has been adequately described with respect to physiological manifestations and widely used in simulation studies.[8,17]

After return to Earth, cosmonauts' physical performance was assessed by evaluating locomotion biomechanics and electromyography parameters as well as by measuring maximum muscle force and strength endurance. Electromyography studies were performed by means of a test offered 60–30 d before and on Days 3 and 10 after flight. The test required walking on a hard platform at a controlled speed of 90 steps/min. The speed was set by a metronome. The cosmonauts were required to carry out every locomotion pattern five times and walked an 8–10 m distance within each attempt. Prior to the test, the cosmonauts were allowed one or two practice attempts to get adjusted to the metronome's rate.

The electromyographic characteristics of locomotion were recorded using the MuscleLab-4000e test apparatus (Ergotest Technology, Stathelle, Norway), which was capable of recording 8 EMG channels at a sampling rate of 100 Hz and sending the data to the computer via Bluetooth. The maximum amplitude of inverted EMGs (iEMG) of the m. soleus was measured. Disposable Ag/AgCl electrodes (Skintact F-301, Leonhard Lang, Innsbruck, Austria) 10 mm in diameter were placed along the muscle belly between the motor zone and the tendon. The distance between electrodes was 20–25 mm. The signals were processed using a Butterworth second-order filter and integrated to calculate means and standard deviations.

The maximum voluntary contraction (MVC) and strength endurance of the leg muscles were assessed using the results of isokinetic tests performed 60 and 30 d before and 4 d after flight. Measurements were made using a Cybex (CSMi Medical Solutions, Stoughton, MA) force dynamometer.

MVC of the quadriceps femoris was measured with respect to knee flexion/extension at an angular velocity of $60° \cdot s^{-1}$. MVC of the m. triceps surae and m. tibialis anterior was determined with respect to ankle flexion/extension at an angular velocity of $30° \cdot s^{-1}$. Strength endurance of the m. quadriceps femoris was evaluated in regards to 22 knee flexions/extensions at an angular velocity of $120° \cdot s^{-1}$. The means and standard deviations of all the parameters were calculated.

RESULTS

The results obtained were analyzed primarily with respect to the parameters that determine the efficacy of on-orbit exercise, viz., axial load, passive mode fraction, and exercise protocol—to be specific, high-intensity running periods.[23] Daily monitoring of the Russian cosmonaut during his 1-yr mission on ISS demonstrated that he adhered to a 4-d microcycle, i.e., during 3 d he worked on a treadmill following the recommendations and on the fourth day he exercised according to his own protocol. His personal protocol included four periods of running at a speed of 12 to 16 km/h, which increased incrementally from period to period, each period being 8–11 min. He allowed himself a pause of 2–4 min between running intervals. When running, his HR reached 129–141 bpm during the first interval, 140–148 bpm during the second interval, 142–156 bpm during the third interval, and 147–157 bpm during the fourth interval. At rest his HR returned to 83–101 bpm. Occasionally, he performed walking and running when the treadmill belt was operated in a passive mode at a speed of up to 7 km/h for 4 min. Thanks to running for long time intervals at a high speed on Day 4 of his personal protocol, KM increased his locomotor exercise intensity on average by 26.6% compared to the recommended level.

The controls followed exercise instructions for Days 1, 2, and 3. As to Day 4, the cosmonauts used different approaches. Three of them preferred a 3-d microcycle, which means that on Day 4 they returned to what they did on Day 1. Two cosmonauts used long intervals of low-intensity running, which was comparable to the protocol kept by KM. One of the six control cosmonauts enjoyed a day of rest, which is allowed by the training program.

Throughout the flight, KM's axial load varied within the range of 48–84.6% of bodyweight; in the control group the parameter amounted to 47–76% of bodyweight. In other words, for KM the lower limit was similar to that in the controls, although during the month preceding the last one of his mission he exercised at a load that exceeded the recommended level by 14 kg (17.9% bodyweight).

For KM, the passive portion of the treadmill belt operation was 20.1% compared with the recommended level of 30% of total treadmill locomotion. It should be noted that the passive portion varied widely: during the first month of his mission the parameter was 10.1% vs. 29.1% during the fifth month (**Fig. 1**). In the controls, the passive portion amounted to 25.3–31.9% of total locomotion load. Again, for KM the parameter was comparable to that for the controls.

Analysis of the reports submitted by KM about his resistive exercise helped identify time course variations in leg muscle loading: at the beginning of his mission the load was 104% when he did squats and 112% of bodyweight when he did heel raises vs. 282% by the end of his mission (**Fig. 2A**). This load

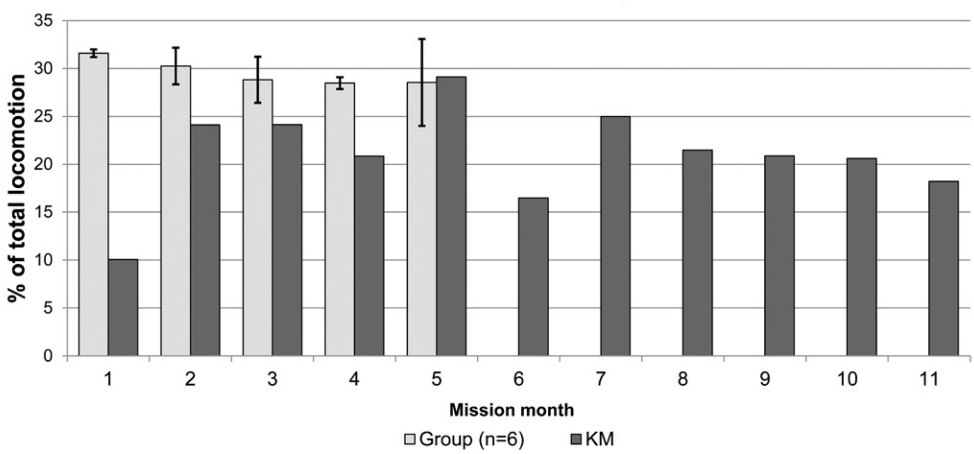

Fig. 1. Passive portion of the treadmill belt operation for KM (who completed a 1-yr mission) and for the group of six cosmonauts who completed 6-mo missions (mean ± SD).

in the resistive exercise was based on KM's individual preferences.

Early in the mission KM performed squats in 3 sets and later 4 sets per training cycle with 15 repetitions in each set. Altogether, the total load per cycle was 5400 kg at the beginning and 17,000 kg at the end of his mission.

He used the same pattern when performing heel raises, i.e., three times at the beginning and four times thereafter. During the early part of the mission the number of repetitions was 15–30, while at the end of the mission it was 100 and more. Altogether, the load varied from 9000 to 134,000 kg per training session (**Fig. 2B**).

During the first on-orbit MO-3 test the physiological cost index grew by 18.4% for KM vs. 3.4% for the controls. During the second on-orbit test the parameter decreased, but still remained higher by 8% compared to the prelaunch level for KM and grew by 9.8% for the controls (**Fig. 3**).

When assessing the efficacy of exercise countermeasures with respect to the stabilization of the neuro-muscular system, it was found that 3 d after landing the EMG maximum amplitude of the soleus muscle increased by 7.8% in KM vs. 5% in the controls. On the 10th postflight day, the EMG maximum amplitude grew by 14.5% in KM vs. 2.6% in the controls.

These findings suggested that, compared to the controls, KM experienced more significant changes in the physiological cost index of the soleus, a highly gravity dependent (postural) muscle. It should be emphasized here that, in spite of the changes, his performance still remained adequate to support autonomous postflight function, as shown by the field tests performed at the landing site.[23]

Isokinetic test results indicated that longer exposure to the space environment impacted the pattern of changes in muscle strength, although the trend toward its decline remained unaltered. Compared to the controls, KM showed more significant changes in the maximum voluntary strength of the leg extensors at an angular velocity of $30° \cdot s^{-1}$ (**Fig. 4**). The decrease in the strength of the leg flexors at every angular velocity measured was similar in KM and in the controls. In KM, the strength endurance of the femoral flexors increased by 19%, whereas that of the extensors remained at the preflight level.

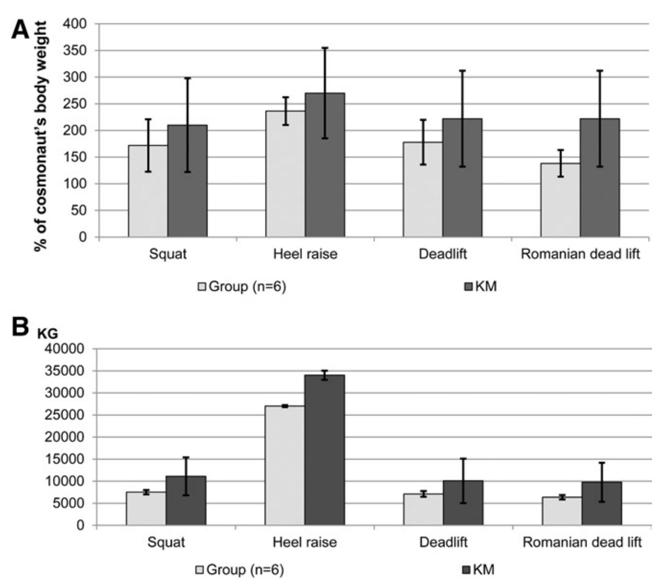

Fig. 2. Load characteristics in resistive training. A) The mean loading weight the cosmonauts experienced in the course of ARED training in space (mean ± SD). B) Average total load per ARED training cycle in space per session (mean ± SD). ARED = advanced resistive exercise device.

DISCUSSION

Our findings are consistent with the current concepts related to the mechanisms underlying the hypogravity motor syndrome. According to the concepts, the lack of gravity reduces the afferent input, which causes a significant decline of

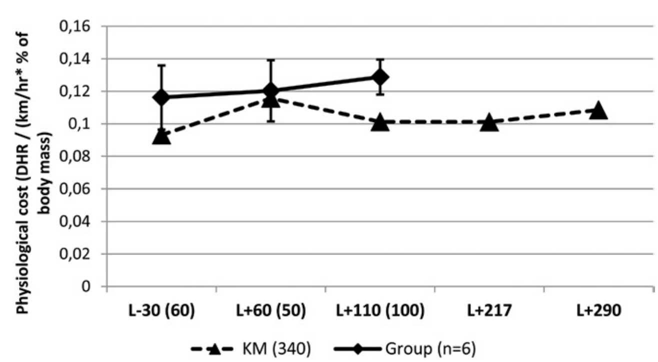

Fig. 3. Physiological cost index in the MO-3 test during the high-intensity running period (mean ± SD) before flight L-30(60) and in flight L+60(50), L+110(100) for KM and the controls, and in flight L+217, L+290 for KM. The control group ($N = 6$) consisted of cosmonauts who completed 6-mo missions. KM (340) accomplished a 340-d mission.

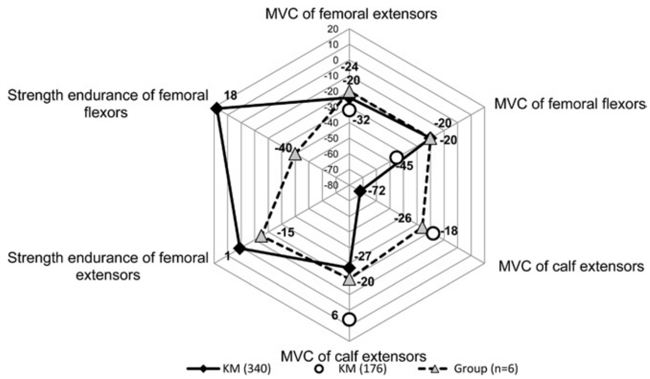

Fig. 4. Variations in the MVC and strength endurance of different muscles throughout the flight. KM (340): data from the 1-yr mission lasting 340 d; KM (176): data from his previous 176-d flight on ISS; MVC = maximal voluntary contraction.

muscle activity that may trigger changes in muscle peripheral structures[11] and motor function.[14] It is believed that the afferent input plays a key role in the regulation of the posture-tonic system and that its reduction or elimination induces lowered activity of the tonic motor units of the extensor muscles and compromised sequence of recruitment of motor units of the motoneuronal complexes of the flexor muscles. This facilitates the function of flexor and phase mechanisms of motor regulation. Thus, our observations indicating a greater decline of the MVC of the calf flexors and a higher strength endurance of the calf extensors recorded in the cosmonaut who was exposed to microgravity for a longer time give support to the current concepts about the mechanisms underlying the development of hypogravity motor syndrome. Nonetheless, our findings may find application in upgrading countermeasures recommended for use in very long space missions, which should help maintain the function of the extensors.

In summary, the Russian cosmonaut who successfully accomplished a 1-yr mission maintained adequate performance throughout the entire spaceflight; moreover, the level of postflight changes he displayed was comparable to that recorded in the group of cosmonauts who completed 6-mo missions. These observations suggest that the Russian system of exercise countermeasures against hypogravity-induced deconditioning demonstrated its efficacy. Further studies and better statistics are needed to make final conclusions. It is hoped that the findings presented in this article will be taken into consideration in future investigations.

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The authors contributed equally to this work.

Authors and affiliations: Elena Fomina, Ph.D., Nataliya Lysova, Ph.D., and Tatyana Kukoba, Ph.D., Institute of Biomedical Problems of the Russian Academy of Sciences, Moscow, and Alexey Grishin and Mikhail B. Kornienko, Yu. A. Gagarin Research and Test Cosmonaut Training Center, Star City, Russia.

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