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Electromyographic evaluation of countermeasures during the terrestrial simulation of interplanetary spaceflight in Mars500 project

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ABSTRACT

The efficiency of six countermeasures (CM) for muscle atrophy was compared over 520 days of confinement during the terrestrial simulation of round space flight to Mars using surface electromyography (sEMG). Three of CM were cyclic exercises (a motor-driven and leg-driven treadmill, cycle ergometer), resistive exercises (the multifunctional dynamometer for space—MDS, and expanders), and vibration platform. Each of CM was applied for each crew member ($n=6$) once over the experiment, for 70 days in a row, in prescribed order. sEMG was collected during the "force step test" in which the subject voluntarily produced pressure by lower limb, with minimal force increment. The mean frequency (MNF) and average amplitude of sEMG were analyzed. The MNF of sEMG decreased from 104.3 ± 4.2 to 95.3 ± 2.9 Hz ($P<0.05$) in the soleus muscle after 70 days of exercising on the leg-driven treadmill and after 35 days—on vibration platform. It can be caused by earlier (10–250 ms) recruitment of the soleus in respect with the medial gastronemius on the leg-driven treadmill, while on the motor-driven treadmill synergists activated synchronously. In other lower leg muscles, MNF decreased from 180 to 200 to 165–180 Hz after 70 days of resistive exercises on the MDS device. CM caused no effect on sEMG amplitude. In conclusion, (1) the leg-driven treadmill, the MDS and vibration platform significantly depressed MNF of sEMG of lower extremity muscles; (2) the leg-driven treadmill and vibration platform specifically affected the soleus muscle. Therefore, these CM can be recommended for a more extensive use on ISS board.

1. Introduction

The manned interplanetary round spaceflight to Mars has long been considered as an awe inspiring mission for mankind [1]. Such a mission is anticipated to last up to 520 days. Long-term space flights provided evidence that humans are capable of withstanding microgravity for at least 438 days [1]. However, microgravity is still one of the limiting factors for the long-term spaceflight because it exerts profound unfavorable effects on all human organ systems [2]. The most readily seen effect of either microgravity or simulated spaceflight on the skeletal muscle system is weakness, atrophy and motor coordination deficits [3,4].

Operating of a spaceship requires precision manipulations using tools, instruments and equipment, while the skeletal muscle and its' coordination system are dramatically affected from very first hours on-board of a space vehicle. The best current preventive countermeasures for microgravity-induced muscle atrophy center around either dynamic (running treadmill, cycle ergometer) or resistive exercises on board of the spaceship [5]. Despite systematic exercise, muscle volume in space flight has been shown to decrease by 13–32% [4,6]. Nonetheless, varied physical exercises are still regarded as a valuable and necessary on-board countermeasure of negative effects of microgravity. Much of the ongoing work is devoted to artificial gravity [7,8] and sensory interventions, such as application of either whole-body [9] or local vibration [5] which has been reported to efficiently decrease muscle atrophy after a long bed rest test. However, there are remaining some blanks to fill in.

It is generally accepted that skeletal muscle constitutes a highly adaptable tissue that responds to environmental and physical stimuli, including age, immobilization, disuse, food restriction, and training [10]. Muscle biopsy-based methods, such as muscle fiber type composition, muscle fiber size, cross section area are widely used to study muscle plasticity. Interference surface electromyography (sEMG) is increasingly used as a reliable non-invasive measure of muscle function under varied environment and physical

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conditions. Both conventional linear and novel nonlinear parameters of sEMG provide relevant information on the motor strategies and help in diagnostics of motor disorders, e.g., Parkinson's disease [27,28], fatigue, atrophy, myopathy, and neuropathy [11,12]. sEMG has been intensively studied under simulated microgravity both in humans and animals [13]. It has been shown that during bed rest sEMG amplitude is decreased [14], and the count of turns is also decreased under hind limb suspension in rats [15]. In the microgravity phase of parabolic flight EMG revealed changes in neuromuscular activation patterns [16]. However, sEMG is rarely used to assess neural adaptations in spaceflight [17].

Spaceflight analogs, such as hind limb suspension in animals, bed rest or dry immersion in humans, and terrestrial spaceflight simulations are widely used to investigate countermeasures (CM) for muscle atrophy, osteoporosis and other unfavorable effects associated with spaceflight [2,5]. The Mars500 project was specially designed to simulate a round interplanetary spaceflight to Mars and back. This study was intended to provide detailed study of varied technical (communication, safety, rescue, and supply), social, psychological, and biological (microbiological, physiological) issues of the interplanetary spaceflight. The comparative study of efficacy of array of CM for muscle atrophy was among the major goals of the Mars500 project. The CM for muscle atrophy based on the cyclic (running treadmill with motor and leg-driven engine; and cycle ergometer) and resistive exercises (expanders and the multifunctional dynamometer for application in space (MDS)), and vibration platform were tested to reveal the most efficient of them in preventing muscle atrophy.

Therefore, the major purpose of our study was to provide comparison of efficiency of the above mentioned CM using the sEMG method.

2. Methods

2.1. Subjects

Six male volunteers aged 34 ± 4 years have participated in the Mars500 study. The facility in which the crew was confined is located in the Institute of Biomedical Problems (IBMP, Moscow, Russia). Prior to the experiments, all subjects were clinically examined and gave their informed consent to all experimental procedures, which were approved by the Human Ethics committees of the IBMP. For their anthropological data see Table 1. Standards set by the *Declaration of Helsinki* were followed.

2.2. Activities over the whole experiment

The 520 days of the experiment were segmented into six approximately 70-day periods, each consisting of combination of 6CM and 3 pairs of subjects. More specifically, each assigned pair of subject underwent all six CM once over the experiment, in even order. The periods of CM were separated by two 35-day periods of rest (the no-exercise condition) and one 35-day imitation of landing and activities on the surface of Mars. The contact with family members was taken only by video channel. For detailed information see Table 2. This design was elaborated and adopted long before the execution of project.

Table 1
Anthropological data of the subjects.

Subject	Age (years)	Body weight (kg)	Height (cm)	BMI
O	38	81	177	25.87
N	37	96	176	31.06
M	32	79	170	27.33
L	30	93	177	29.71
K	27	81	180	25.00
I	27	71	175	23.20

BMI—body mass index.

2.3. Countermeasures (CM)

The Russian system of preventative therapy is based on few key points: (1) high diversity of CM, (2) their high intensity, (3) combination of static and dynamic exercises, and (4) periodicity [5,18].

1) The leg-driven treadmill is a non-motorized treadmill with man-powered movement of the circular endless belt. A mechanism is rotated by walking/running on a circular belt while staying in the same place. This treadmill (BD-1) appears as a regular non-commercial CM on the Russian segment of the International Space Station (ISS). This running protocol was designed with speeds varying between 5 and 14 km/h, and on average exercising on the motor-driven treadmill had occupied 33 ± 14 min. In the first half of the cycle, power use increased, and decreased in the second half.
2) The motor-driven treadmill—a motorized commercial treadmill with engine-powered movement of the conveyor belt (CYBEX 750T, Medway, USA). Physical exercises on the motor-driven treadmill were based on the 4 day cycle, which consisted of 3 days of training (the training described in the board documentation) and one day of "active" rest when the crew members were allowed to choose the intensity and duration of the training [5]. Thus, exercising on the motor-driven treadmill also consisted of 33 ± 4 min walking and running at varying speeds using a protocol adopted for Russian cosmonauts on ISS (for details see Ref. [18]).

Table 2
Logistics of exercise protocols over the 520 days of the Mars500 project.

Crew member / day	1-35	36-70	71-105	106-141	142-177	178-213	214-250	251-284	285-319	320-354	355-389	390-424	425-450	451-485	486-520
O															
N															
M															
L															
K															
I															

Shaded: expanders; dark grey: multifunctional dynamometer for space; light grey: vibration platform; horizontal strips: running on motor-driven treadmill; vertical strips: cycle ergometer; white: running on leg-driven treadmill; black: pause in training; grid: simulation of work on the surface of Mars.