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Pathophysiology of motor functions in prolonged manned space flights

I. B. KOZLOVSKAYA, YU. V. KREIDICH, V. S. OGANOV AND O. P. KOSERENKO
Institute of Biomedical Problems, Ministry of Health, Moscow, U.S.S.R.

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Abstract—The influence of weightlessness on different parts of the motor system have been studied in crew members of 140 and 175 days space flights. It has been shown that weightlessness affects all parts of the motor system including (i) the leg and trunk muscles, in which severe atonia, a decrease of strength and an increase of electromyographic cost of contraction have been observed, (ii) the proprioceptive elements and the spinal reflex mechanisms in which decreased thresholds accompanied by decreases of maximal amplitude of reflexes and disturbances in cross reflex mechanisms have been found, and (iii) the central mechanisms that control characteristics of postural and locomotor activities. The intensities and durations of disturbances of different parts of the motor system did not correlate to each other, but did correlate with prophylactic activity during space flight. The data suggest a different nature of disturbances caused by weightlessness in different parts of the motor system.

1. Introduction

Among the many disturbances induced by a decrease in G-loads, disorders in functions of the musculoskeletal system and systems of motor regulation are of great importance. Studies in weightlessness and under simulated weightless conditions have shown that a weightlessness-dependent motor syndrome is characterized by changes in all parts of the motor system. On short-term exposures it manifests itself as decreased muscular tone and strength of muscle contractions, muscular hyperreflexia[1], coordination disturbances with decreased accuracy of execution of muscular efforts, increased motor reaction time, and a change of biomechanical structure of locomotion[2, 3]. On longer duration exposures, the pattern of motor disturbances is complicated by the development of atrophic processes in the muscles[4], by more profound shifts in the reflex system, by significant coordination disorders with a sharp decrease in upright posture stability, and by major changes in locomotion and alterations in body perception[5, 6]. The data are mainly descriptive and scattered, providing the basis for a number of hypotheses involving different factors, for instance, muscular atrophy, changes in gravireceptor activity, alteration in the mechanisms of motor integration, etc., as the major cause in the disturbances mentioned. However, none of the hypotheses is experimentally tested and substantiated to date.

In order to understand the motor disturbances caused by weightlessness, it is necessary to obtain qualitative data regarding the state of different parts of the motor system during various periods of time following an exposure to weightless space flight and during readaptation to G-loads.

Proceeding from this prerequisite, a program has been developed to study the cosmonaut motor system; this included a number of techniques and tests to assess quantitatively the state of the muscular system and main proprioceptive inputs, skeletal and muscular ones, some spinal mechanisms and the movement control system.

This test battery was used to investigate the motor system of cosmonauts participating in the 140 and 175 day space flights.

2. Experimental procedures

2.1 *Muscular system*

It is known that the relationship between a muscle-exerted force and magnitude of the integrated electromyogram (EMG) is of linear character[7], and that with a decrease the muscle contraction capabilities, the amplitude of the EMG increases on executing a standardized effort, due to the increase in the number of motor units involved in contraction, both in frequency and synchronization of their discharges.

Based on this a "Myotest" procedure was used to evaluate the state of the leg and thigh muscles; the major index of the functional muscular state is a coefficient of electromechanical efficiency, calculated as a ratio of integrated EMG magnitude to the amount of standard load. For the leg muscles a pedal spring, and for the thigh muscles, an ankle-mounted additional load set this standard load. The leg muscles were tested with a series of foot movements of small amplitude and strength. A lamp switching on served as a signal to start a movement; switching off was indicative of reaching the preset amplitude. The experimental load magnitude was 5 and 7 kg, which with use of a given amplitude of movement, did not exceed 8–12% of maximum strength. The movements were executed with dynamic and static components. The angle of the movement and the EMG of the gastrocnemius and anterior tibia muscles were recorded. When testing the muscles of the thigh, the test subject executed a motion of bending the leg at the knee joint, starting from 120° (position on the couch) to complete straightening with a subsequent maintenance of this position for about 5–8 sec.

Since the relationship between the EMG magnitude and strength under natural conditions changes depending on initial muscular length, testing was always performed with supine test subjects and fixed adjacent joints in the tested extremity.

In the 175 day space mission, the program to investigate the muscular properties also included isokinetic dynamometry using a "Cybex" dynamometer. Testing included an evaluation of rate-strength properties of the leg, thigh and back muscles on the basis of indices for the moments of forces and on the basis of the EMGs of working muscles under conditions of high (180°/s) and low (60°/s) contraction rates and isometric contractions. In the case of dynamometry (as opposed to all other tests) data on rate-strength properties of the muscles of six healthy subjects participating in model experiments served as the controls.

2.2 *Sensory systems*

Function was determined using the threshold of vibration sensitivity of the supporting zones of the sole. Pacinian corpuscles highly sensitive to stimulation by vibration are concentrated in the subcutaneous fat of the medial and lateral pads of the foot, in the calcaneal tuberosity and in the pad of the great toe [8]. At these points the thresholds of sensitivity to vibration were recorded by a "Vibrotester" device at three frequencies of stimulation: low—63 Hz, moderate—125 Hz, and high—250 Hz.

Evaluation of the state of muscular input and associated mechanisms of spinal regulations was based on determining the parameters of the recruiting curve of the gastrocnemius tendon reflex (Achilles T-reflex). Selection of this test was based on its simplicity and informative value. The tendon reflexes of man are well understood, are monosynaptic, and their role in muscular reception has been documented in numerous studies [9].

To plot a recruitment curve showing dependence of reflex amplitude on the intensity of stimulation, calibrated impacts on the tendon have been used. A hammer with a built-in sensor for recording the impact intensity was used. Electromyographic responses of the gastrocnemius and anterior tibia muscles were recorded using surface electrodes (Fig. 1). The recruitment curve was analyzed for thresholds of reflex response, maximum amplitude and steepness of gain. The data [10] show that the above parameters are not interrelated and present different properties of the motoneuronic system: an excitability of the threshold and maximum amplitude elements and homogeneity of population reflected by the amplitude gain gradient.

Comparison of the characteristics of the recruitment curve at rest, while the other leg executes dorsal and plantar bends, has allowed assessment of crossed synergies, one of the major mechanisms of locomotor activity.

2.3 *Motion management systems*

The stabilographic data and results of posture synergy investigations indicate the status of the movement management system. To record the stabilograms, a

Fig. 1. Original records of T-reflex of the gastrocnemius (shown by GM line) and Tibialis anterior (shown by TA line) muscles.

stabilographic platform, amplifiers and pen recorder were used. Recording was performed in a standard way[11] for 3 min (but for 6 min before flight): First minute—a comfortable position with eyes open; second minute—the same position with eyes closed; third minute—Romberg posture. The electromyogram of the leg muscles was recorded at the same time. The stabilogram was analyzed for the frequency of oscillation of the body center of gravity, calculated as a per cent of oscillation on a control test. The stability was also determined after equilibrium recovery by applying perturbations resulting in equilibrium loss. External perturbations were produced by means of graded impacts on the chest of the test subject; the voluntary perturbations resulted from a test task in which the test subject lifted the heel of one leg in response to a signal, either sharply or slowly, without taking the toe off of the support.

Voluntary and external perturbations of equilibrium are prevented and corrected by activity of the muscular apparatus. Complex motor reactions precisely organized in time and space, which provide the body stability, are called "posture synergies"[12]. By studying the amplitude and duration of the EMG discharges of the leg muscles while standing, with and without perturbation, the state of posture synergy management could be assessed qualitatively and quantitatively.

Investigations were performed before, on the 2nd (3rd), 5th (6th), 9th (11th), 25th and 35th (42nd) days after the flights. Preflight investigations served as baseline.

3. Experimental results and discussion

3.1 *Muscular apparatus*

Anthropometric and neurological examinations of the crew members of the 140 and 175 day flights (2nd and 3rd expeditions) did not reveal marked changes in masculature except for a pronounced atony of the posterior group of leg muscles, atrophy of the long dorsal muscles in the flight engineer of the 2nd expedition (FE-2) and some subatrophy of the widest dorsal muscles in the crew members of the 3rd expedition. The atony was of short duration; the symptoms did not increase past 5–6 days and on the 11th day could not be detected.

Measurements of the circumference of extremities on the first postflight day revealed a small decrease in leg circumference; however, these changes were short-lived. When these circumferences were measured in the middle of the 3rd day in upright position (as performed preflight), the leg circumferences in the FE-3 were equal to preflight, and in the CDR-3, it differed from preflight only by 0.5 cm. The relatively small losses of weight of the FE-2 and CDR-3, and the lack of such losses in CDR-2 and some weight gain in the FE-3 suggested that the crew members of both expeditions had no great muscular losses inflight. However, physiological testing revealed the marked changes in the muscular system. According to the "Myotest" data in both cosmonauts of the 3rd expedition, the electromyographic cost of a standard exertion by the posterior group of leg muscles increased more than twice after the flight. This increase, being particularly pronounced when working statically, could still be seen at 35 days postflight, having reached a peak of increase on the 6-11th days in the postflight period (Fig. 2). In the crew members of the 2nd expedition, myotest indices were more variable; the CDR-2 showed a significant increase in the cost of the gastrocnemius strength when executing the static test. This increase was stable and maintained up to the 42nd postflight day. The FE-2, who had similar variable data in anthropometric and clinical examinations, showed muscular changes that were poorly defined, and as a consequence the "Myotest" results were more mixed.

More definite changes in muscular properties were found using isokinetic dynamometry. According to the dynamometric data, both crew members of the 3rd expedition showed considerable decrease in gastrocnemius strength characteristics, especially marked when working in the isometric and high rate (180°/s) regimens. In the CDR the magnitude of force deficiency was somewhat higher and its compensation was more slow: during 8 postflight days the gain in maximum effort was only 25–30%. Strength indices of the thigh muscles in both cosmonauts were within norm (Fig. 3).

It should be noted that similar changes in strength indices were also noted in crew members of short-term expeditions and in test subjects after a 7-day immersion. The latter study suggests the significant rọle of tonic and afferent shifts in developing the muscular disturbances.

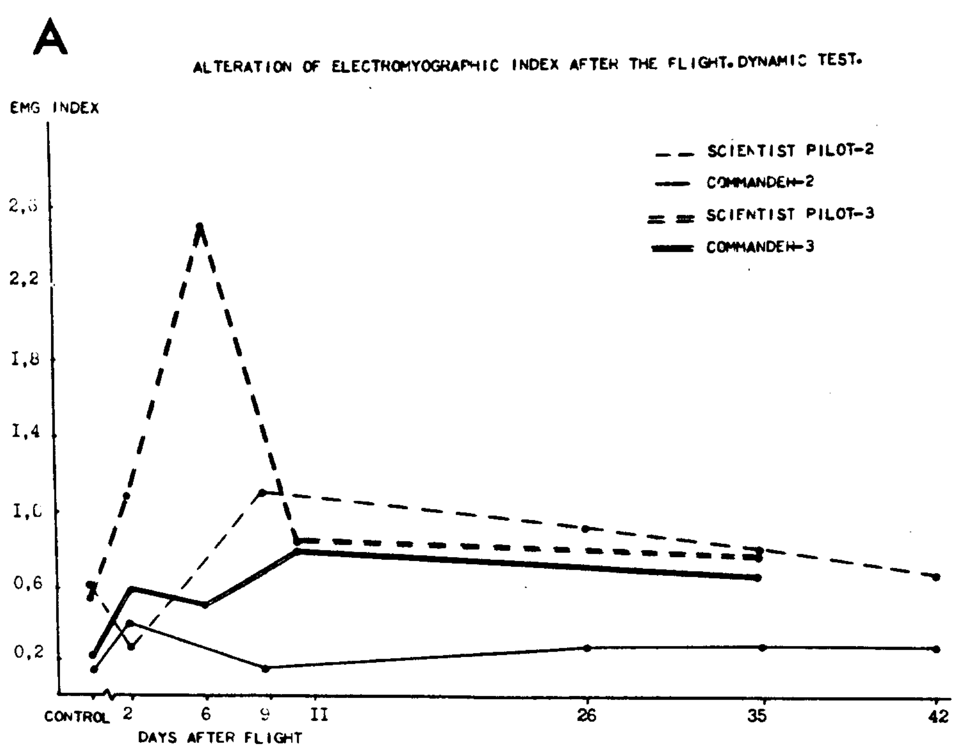

Fig. 2(A).

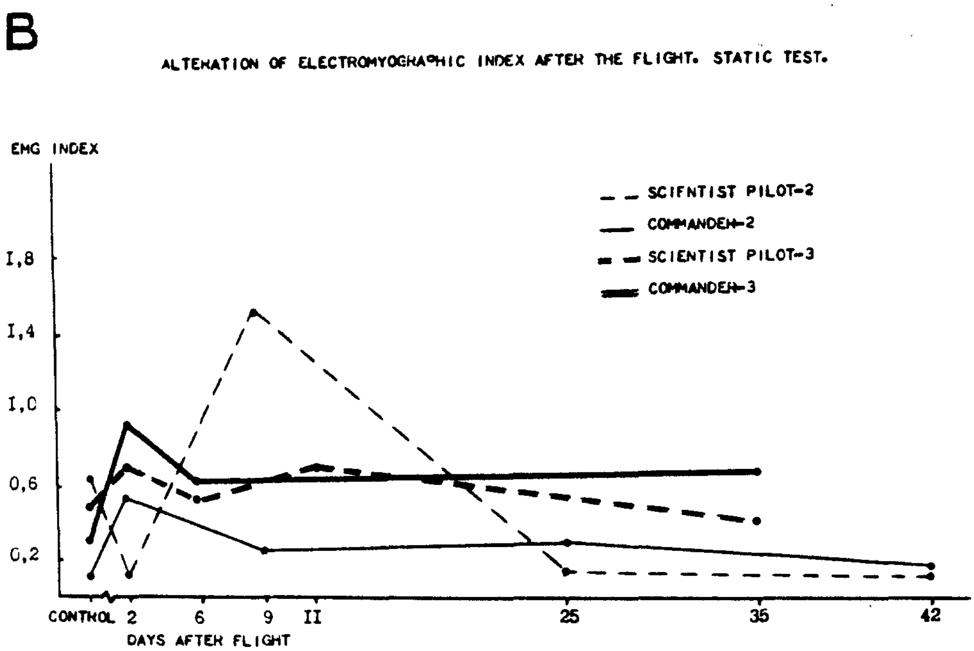

Fig. 2. Changes in electromyographic index after space flight. (A) The data of the dynamic test. (B) The data of the static test. The EMG index shows the relation between the amplitude of integrated EMG and the muscle force developed during performance of the dynamic and static motor tests.

3.2 *Sensory systems*

The tests used have revealed a clear tendency toward hyperactivity of sensory systems in all the crew members of these long-duration expeditions. In the CDR-2 on the 2nd postflight day, a considerable decrease in the thresholds of vibration sensitivity of the supporting zones of the foot was noted; the increase in sensitivity was stable and manifested at all frequencies up to 25th day and at 63 and 125 Hz frequencies up to 42nd day.

Similar changes in vibration sensitivity of supporting receptors were found on the 3rd and 6th postflight days in the CDR-3.

At the same time, in all the crew members of the long-duration expeditions a sharp decline in the tendon (T) reflexes thresholds was observed. The postflight thresholds were 200 g (CDR-2), 300 g (FE-2) and 500 g (CDR-3) instead of the 1000 g and more observed preflight. In contrast to the usual state of hyper-reactivity, the threshold decrease was associated with a decline in maximum reflex amplitude and gradient of gain. These changes were longer lasting than the thresholds and showed a tendency to recover at 5–6 postflight days.

Interextremity reflex relationships such as voluntary extension of the gastrocnemius of the opposite leg (dorsal bending) usually caused inhibition of reflex preflight, but postflight had no effect on the parameters. Duration of these changes was quite different and ranged from 9 days (CDR-2) to 36 days or more (CDR-3) (Fig. 4).

Summarizing briefly, extended space flights considerably increased the reactivity of the basic proprioceptive inputs. This increase in sensory system sensitivity can be caused both by change in the properties of the receptive apparatus and in changes in sensitivity of centers receiving the signals. Observation of similar decreases in reflex muscular response thresholds after immersion-induced hypokinesia support the last statement[13]; here the excitability of the motorneuronal pool is tested using the H-reflex method, in which stimulation is addressed not to the receptors but directly to the motor neurons. However, in our experiments, when comparing effects of immersion on the parameters of T- and H-reflexes, changes in the thresholds of the former were more characteristic and sometimes more profound than those of the latter.

3.3 *System of motor regulation*

Disturbances in motor activity control in crew members of the 2nd expedi-

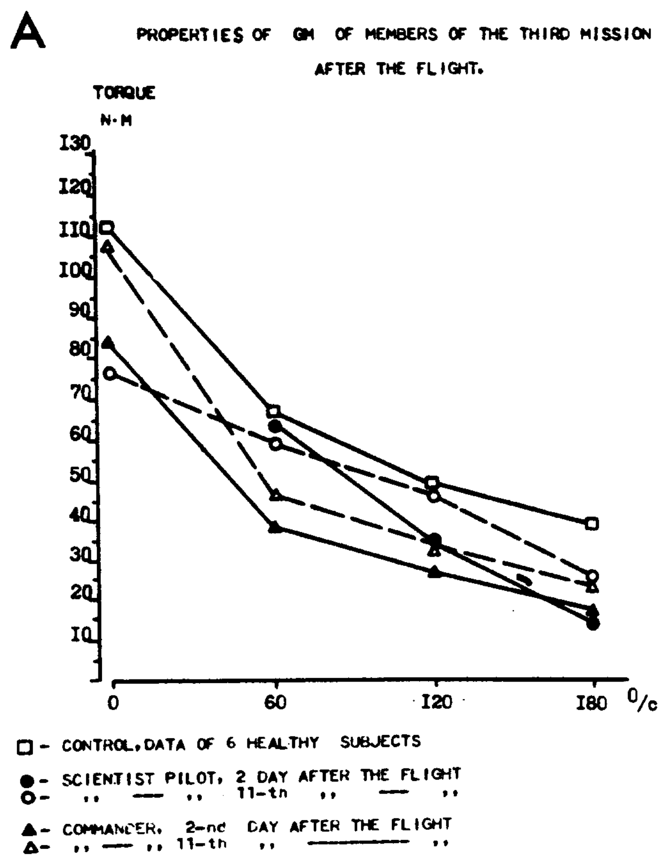

Fig. 3(A).

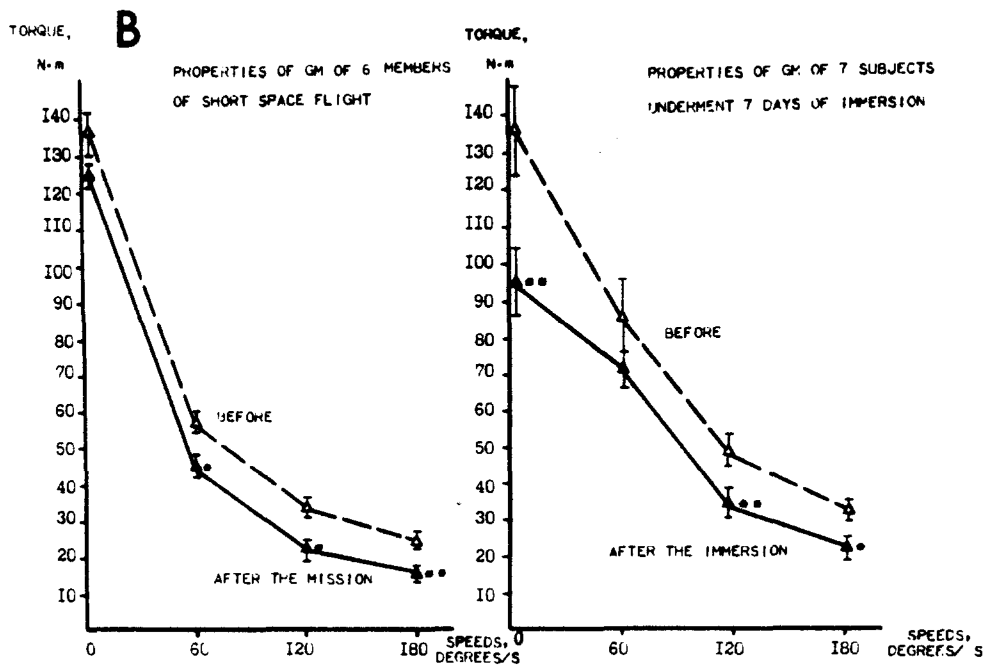

Fig. 3. Changes in muscle force after space flights. (A) The data of crew members of the third prolonged mission. (B) The data of crew members of short space flights (shown on the left) and subjects participating in immersion experiments (shown on the right). The figure shows relations between different speeds of movements (shown on the abscissae) and size of maximal torque developed during isokinetic exercises.

tion were major and of long duration. The very first studies revealed marked changes in the stabilographic curve: although preflight characterized by polymorphic variations, including the first-, second-, and third-order waves, postflight high frequency variations such as tremor, recorded both under no-load and loaded conditions, became dominant (Fig. 5). In the EMG of gastrocnemius and anterior tibia muscles, these variations were grouped at a frequency of 8–9/s. Electromyographic bursts in body upright position exceeded control values by more than twice, reaching 200 mV and more; in this case the gastrocnemius activity predominated in the CDR and the anterior tibia in the FE. The latter resulted from the atrophy of long dorsal muscles and the atrophy-based development of incorrect posture.

Changes in posture stability were more major on performing the tests with perturbations. The time to recover equilibrium both with external and voluntary disturbances of the equilibrium position increased significantly. Recovery of the position of the general center of gravity of the body was accomplished using overregulation.

Electromyographic analysis of correcting responses to the perturbations indicated that decrease in vertical stability was closely associated and likely caused by major synergy disturbances in posture maintenance. Electromyographic response preflight to graded impacts on the chest was characterized by high amplitude bursts of flexors occurring with a latency of 60 μs, and by inhibition of extensor EMGs, which began somewhat earlier and lasted longer than flexor changes (Fig. 6).

Amplitude and duration of the correcting response showed a direct dependence on strength of stimulation: thresholds for responses were 6 kg and more.

Postflight, the thresholds for correcting responses decreased markedly,

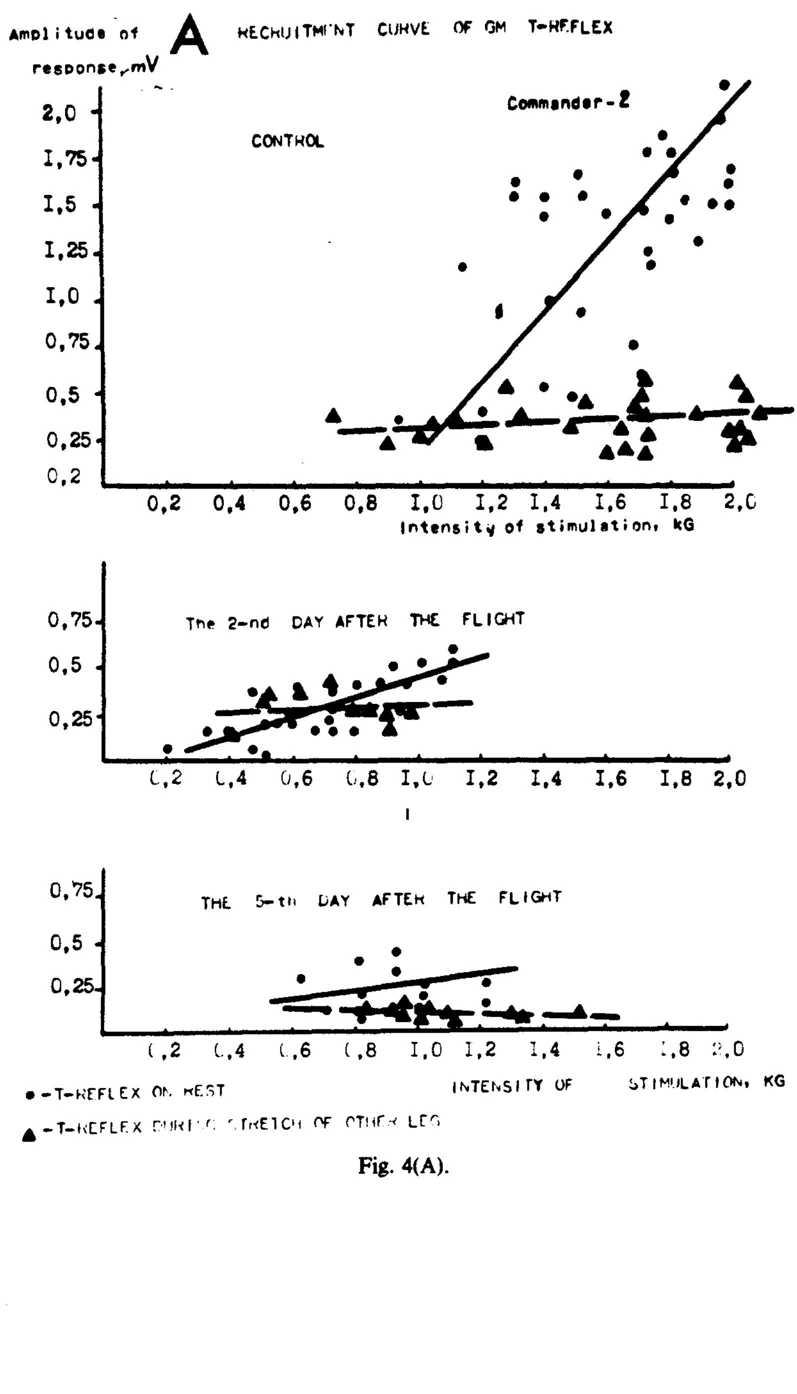

Fig. 4(A).

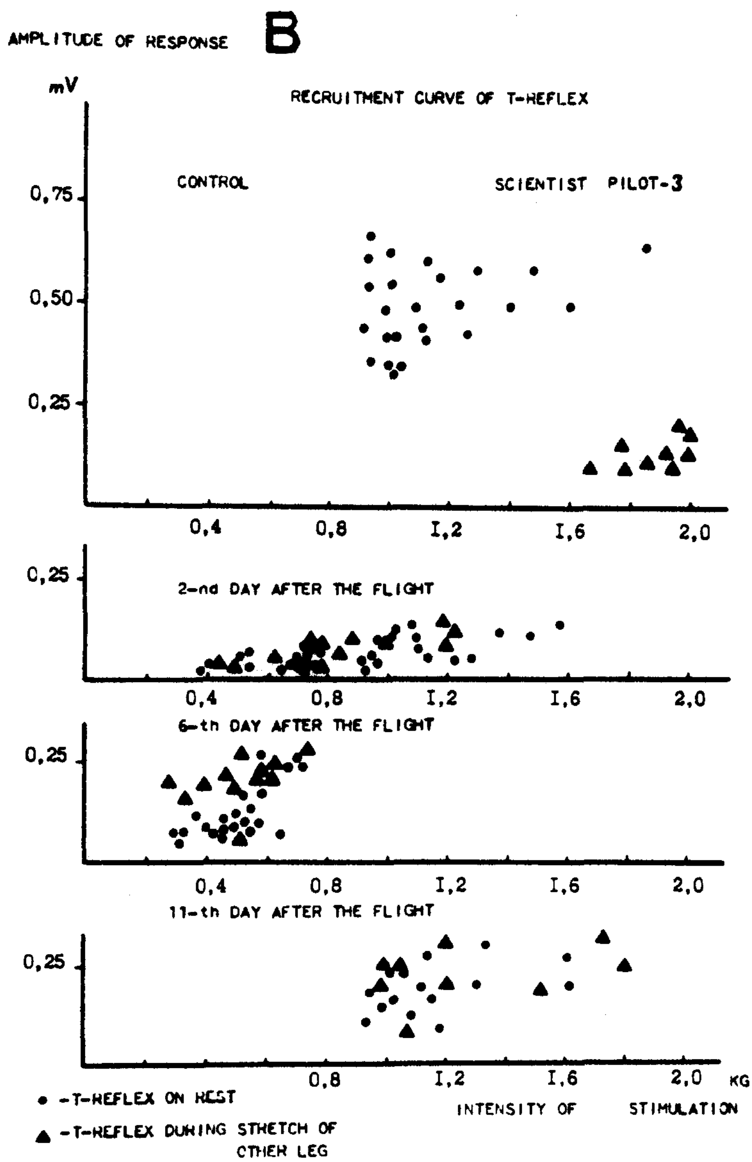

Fig. 4. Changes in the parameters of the recruitment curve of T-reflex of the gastrocnemius muscle after space flights. (A) The data of the commander of the second prolonged mission. (B) The data of the scientific pilot of the third prolonged mission. The force of the tap is shown on the abscissae, the amplitude of EMG response on the ordinate.

reaching 3 kg and less; in this case amplitude and duration of responses sharply increased the extensors and the flexors functioned simultaneously. When executing voluntary tilts, the posture rearrangements to provide stability to the body were

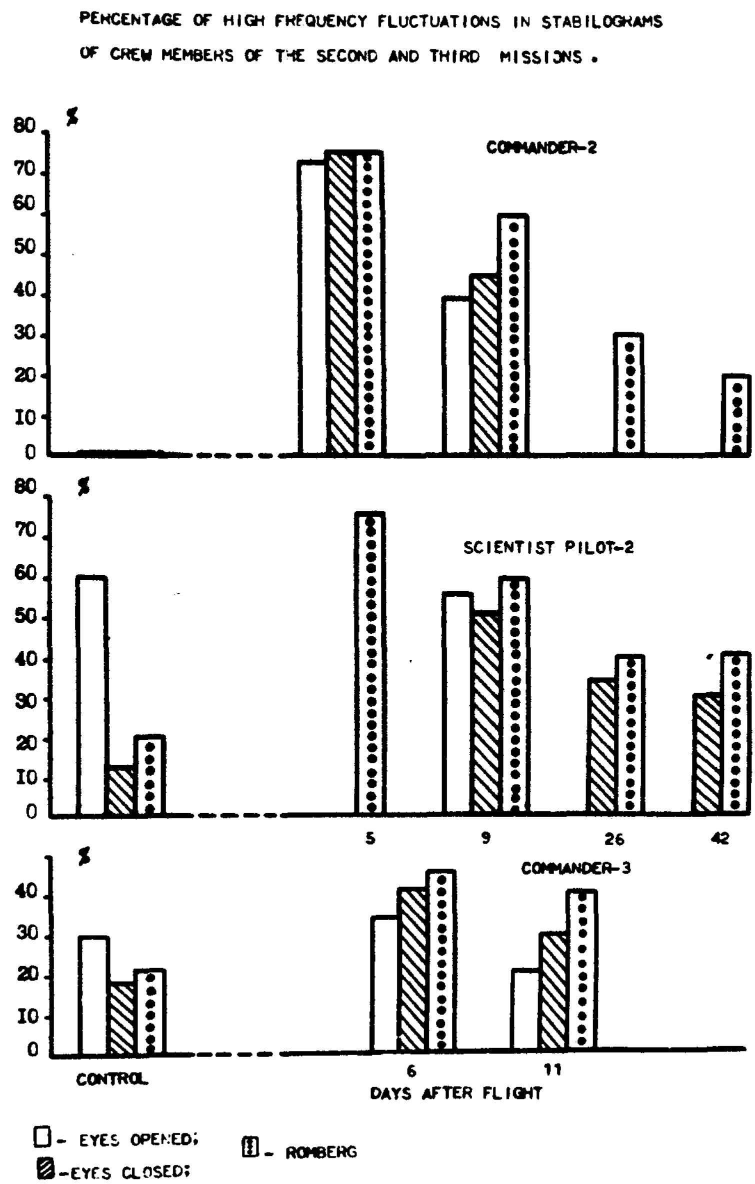

Fig. 5. Percentage of high frequency fluctuations in stabilograms of crew members of the second and the third prolonged flights.

performed with great delay (400–500 μs vs 200 μs preflight); their pattern, amplitude, and duration did not correspond to parameters of local motion and, therefore, failed to provide good stability. Changes in the posture synergy were similar in both crew members; however, the FE amplitudes of flexor electromyographic bursts were not significantly increased, as for the CDR, but rather

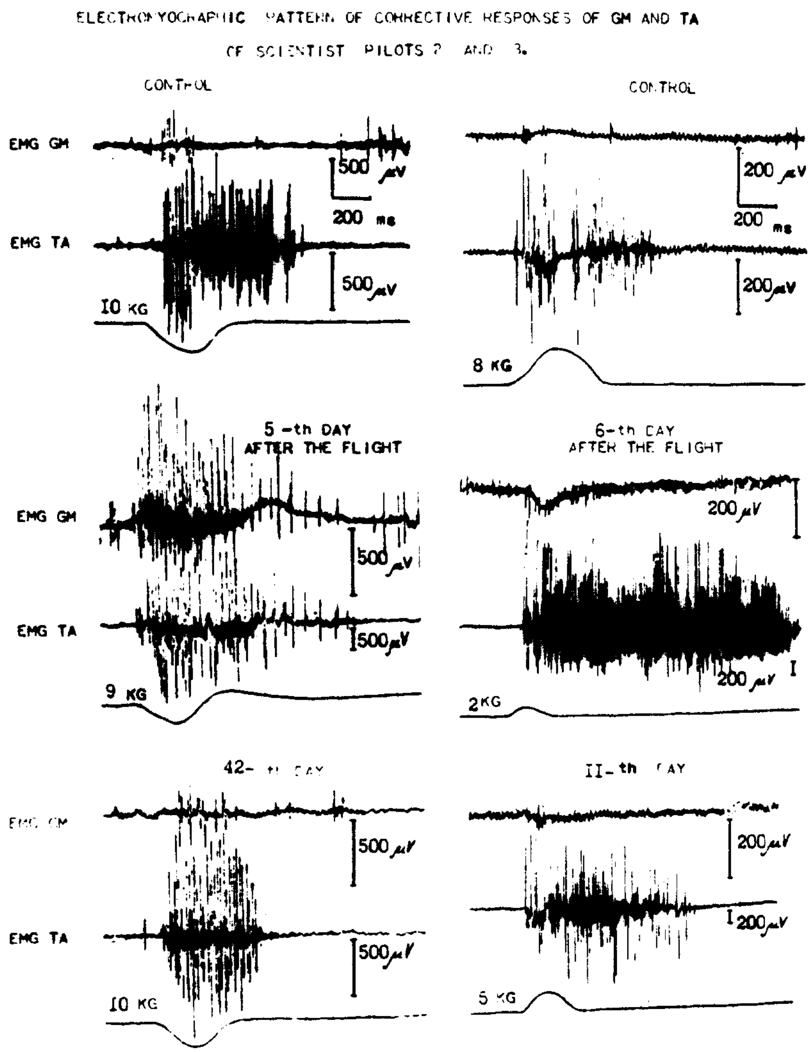

Fig. 6. Changes in electromyographic patterns of corrective responses of GM and TA evoked by external disturbances after prolonged space flights. The lower line in every fragment shows the intensity of disturbances.

decreased, and the disturbances of posture synergy on voluntary tilts were more profound. The shifts while executing voluntary tilts were constantly detectable, gradually diminishing to day 42.

Changes in the activity of the posture control systems in the crew members of the 3rd expedition were similar; however, their magnitude was significantly less.

4. Conclusions

In conclusion, the studies demonstrated an independence of the shifts induced by a long stay in weightlessness on the different parts of the motor system. In crew members of the 140-day expedition, more significant and long-term changes were noted in the system of posture and locomotion control; in crew members of the 3rd expedition there were shifts in the state of proprioceptive inputs and in spinal reflex mechanisms. The data indicate independent disturbances in the activity of different components and consequently, differences in etiology.

That the effects of weightlessness on the motor system are multiple and varied is natural. The motor apparatus of the terrestrial animal has evolved phylo- and ontogenetically under conditions of gravitational forces and is organized in response to this. This organization is complex and includes many definite structural and functional mechanisms, which provide reliable stability and prerequisites for work in Earth's gravitational field. In the motor sphere lack of gravity is associated with a number of factors which affect individual mechanisms and the motor system as a whole. Besides the prime unloading of the support and motor apparatus, these are: (a) a new distribution of forces along the surface of the body and, associated with this, suppression of the supporting reactions which normally play an important role in the system of postural and tonic regulations [14]; (b) change in the function of the afferent systems, causing, in turn, alterations in sensory signals for motor reactions; and (c) change in the biomechanical structure of movements possible in the unique sphere of weightlessness. Since the structure and function of the motor system are inseparably linked, the above coordination changes in flight might cause after a definite duration the development of major structural changes in the muscles, neuromuscular synapses and other parts of motor system, something that probably takes place when prophylactic measures are insufficient and inadequate.

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