

## Influence Of Long-Term Space Flight On Mechanical Properties Of The Human Triceps Surae Muscle: Electro Mechanical Delay And Musculo-Tendinous Stiffness

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### ABSTRACT:

The effects of long-term space flight on human triceps surae (TS) muscle function and electromechanical delay (EMD) have been investigated. Voluntary and electrically evoked contractions of the TS were obtained from 7 male cosmonauts 30 days before and 3 days after landing. For all cosmonauts the isometric maximal voluntary contraction was reduced by 41.7 % ( $p < 0.01$ ), whereas the electrically evoked maximal tetanic contraction force ( $P_0$ ) was found to decrease by 25.6 % ( $p < 0.05$ ). Force deficit increased by 50 % ( $p < 0.001$ ). This suggests that most of the force loss is due to a reduction in motor drive (motor control). The decrease in  $P_0$  was associated with a significant increase of the corresponding maximal rates of tension development (43.7 %). The twitch tension ( $P_t$ ) was not significantly changed and the  $P_t/P_0$  ratio was increased by 46.7 % ( $p < 0.05$ ) after space mission. The twitch time-to-peak tension of the TS increased by 7.7 %, but half-relaxation time decreased by 20.6 %. Force-velocity properties of the TS calculated according to a relative scale of voluntary contraction development significantly decreased. The calculations of the same properties of electrically evoked contraction development did not differ substantially from the initial physiological state. Total reaction time (TRT), pre-motor time (PMR) and motor time or EMD were determined. In response to a supramaximal single electrical pulses applied to the tibial nerve, the latent period between the M-wave and  $P_t$  beginning was determined. The voluntary contraction EMD increased by 34.1 %; but PMR and TRT decreased by 19.0 and 14.1 %, respectively. The EMD of electrically evoked contraction did not significantly change. Thus, the comparison of the mechanical alterations recorded during voluntary contractions and in contractions evoked by electrical stimulation of the motor nerve, suggests that weightlessness not only modifies the peripheral processes associated with contractions, but also changes central and/or neural command of the contraction.

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## I. INTRODUCTION

Many properties of the skeletal muscles are known to be altered by an exposure to conditions of weightlessness. Observations from the «Skylab» missions, and more recently the US «Spacelab» and Soviet/Russian Space Station «MIR» missions, have shown weightlessness not only to induce muscle atrophy and decline of muscle strength, but also to reduce the physical work capacity and increase the fatigability of the crew (18). In prolonged space travel, these contractile properties alterations could limit the crew's ability to work in space and/or on the surface of Mars and to rapidly egress in an emergency on return to Earth. The countermeasures employed during space flights have not been completely successful in preventing reductions and alterations in neuromuscular performance (23, 29, 57).

Changes in contractile properties produced by microgravity are complex. Numerous observations have supported these initial expectations. It was clear from the earliest short-term flights that neuromuscular function was negatively affected by flight (2, 18, 21, 32, 68). After a 17-day «Shuttle» space flight (STS-78), Narici et al. (68) studied muscle function shown that maximal voluntary contraction (MVC) of the plantar flexors was not significantly altered during space flights, the peak tetanic torque elicited by 50 impulses  $s^{-1}$  direct electrical stimulation showed a decline during space flight (10 %). Widrick et al. (86) determined the peak force of individual slow type I and fast type IIa fibers of the soleus and gastrocnemius muscles in four crewmembers on the same space flight (STS-78). The peak force dropped by 21 % in type I fiber and by 25% in type IIa fibers from the soleus muscle. The single fibers from the gastrocnemius (both type I and IIa) were less affected than the soleus muscle fibers (25). The authors suggest that plantar flexor force is lost by 17 days in space, and that the soleus muscle contributes more to the decline than the gastrocnemius. «Skylab-2» (28-day mission) showed a greater drop in thigh *vs.* arm and extensor *vs.* flexor torque, with the peak extensor torque of the thigh declining by 20 % compared with a 10% loss in thigh flexor and arm extensor groups. «Skylab-3» (59-day mission) showed an even greater difference between the microgravity-induced loss in thigh (mean 20 % drop) and arm torque (mean 2 % drop) than Skylab-2. The differences were

ameliorated on «Skylab-4» (84-day mission), in which the leg exercise countermeasures were credited with reducing the mean loss of peak thigh torque to 6 % (32).

Similar neuromuscular functional tests were performed during long-term space flights (2, 4, 55, 57). In longer «MIR» flights of 6-mo duration, three cosmonauts shown a 20-48 % decline in the MVC of calf plantar flexion (89). After 237-days in space flight, both ankle dorsiflexion and plantar flexion strength were significantly reduced (34). Antonutto et al. (5) demonstrated peak force during two-legged extension to decline by 26 and 29 % after 169, and 180-days in microgravity, respectively. In the previous study (45, 47, 55, 57) we have shown that long-term voluntary bed rest (a 120-day) or long-term space flights (a more 120-days) of the triceps surae muscle produced a significant increase in the time-to-peak tension, and a reduction in MVC, and the maximal strength of a stimulated contraction. The decline contractile properties (in muscular strength) observed in «Skylab» astronauts and Soviet/Russian cosmonauts occurred despite in-flight countermeasures (e.g., treadmill, cycle ergometer, lower body negative pressure). Decrements in motor performance could have negative implications for effective completion of mission-critical operational tasks. None of these studies, however, provide any insight as to whether the space flights-induced decrements in neuromuscular function were of a neural or a muscular origin.

Surface electromyogram (EMG) data show the electrical activity of muscle and have been used in the analysis of human movement. The electromechanical delay (EMD) is traditionally defined as the time lag between the onset of muscle electrical activation and the onset of force production (15). Muscle force is registered only when the contractile elements of the muscle shorten, thus stretching the series elastic components (SEC), which participates in the transmission of force to tendons and joints (38). If the contraction strength changes, significant changes are seen in the EMD values and, therefore, in the SEC (65). This confirms the idea that the time until the SEC stretches is a primary EMD determinant. Furthermore, the SEC structures, originally consisting of an active part (located in the myofibrillare) and a passive one (represented mainly by the aponeurosis and tendon) (88), may contribute to the

EMD value.

The EMD changes can be attributed to changes in muscle SEC stiffness. Muscle stiffness is described as the ratio between the force and length of stretching. A mechanically stiff muscle will transmit more force if the SEC stretches a small amount and, on the contrary, mechanically "gentle" (or "slack") tissue requires a significantly stronger muscle contraction in order to stretch the SEC and produce measurable force. "Slack" tissues require more time from the moment of activation to the start of force generation, i.e. their EMD is longer and it is shortened when muscle stiffness is increased before muscle tension (67). Therefore, the EMD may become a criterion for the differences in stiffness of the musculo-tendinous complex (MTC) under different conditions.

Musculo-tendinous stiffness (MTS) is known to increase after of strength training (35), and it may therefore be expected that the EMD would be shorter in those subjects who practiced physical training in microgravity conditions (54), compared to those who were not subject to physical training (53).

Most of the information on unloaded muscle function in humans has been obtained from ground-based simulation of weightlessness (i.e., bed rest, unilateral lower limb suspension, «dry» water immersion). These studies have shown that muscle strength is reduced by 12-30 % (1, 2, 34, 44, 45, 50). These studies have shown changes in muscle that appear to mimic those observed with 0 G (6). However, studies providing information that directly compares skeletal muscle characteristics during space flights and ground-based analogs of simulated weightlessness have not been conducted. We studied seven crew members before and after of long-term space flights (a more 120 days) Space Station «MIR» mission. We also studied eight subjects after of a 120-days strict bed rest in an antiorthostatic position (-6°) head-down tilt in normal adult subjects (47, 49).

The work presented here is the first study to make quantitative measurements of the contractile properties of the skeletal muscle in men exposed to long-term space travel. The investigation was concerned with the mechanical responses of the triceps surae (TS) muscle. The calf muscle was chosen because it is believed to be one of the skeletal muscles most affected

by microgravity unloading because of its postural role in a 1-G environment (13). Mechanical and electrical parameters were recorded during electrical stimulation of the muscle motor nerve to distinguish peripheral changes from those occurring centrally.

Up to now, due to methodological difficulties, examination of the intrinsic contractile properties of human skeletal muscles in a true weightless environment and/or during its simulation has been beyond the capability of scientists who have therefore concentrated mostly on investigating the mechanical features of the voluntary muscle contractions. The primary goal of the present work was to use single muscle to determine whether mechanisms of human muscle contraction were affected by prolonged space flight. Since we had previously used identical methodology to investigate the effects of a long-term period of bed-rest on the human TS muscle function (36, 42), our secondary goal was to test the validity of ground-based bed-rest as a model of human space flight.

## II. METHODS

The experimental protocol was approved by the Russian National Committee on Bioethics of the Russian Academy of Sciences and the Yu. A. Gagarin Cosmonauts Training Center at Star City and was in compliance with the principles set forth in the Declaration of Helsinki (last modified in 2004).

### *Participants*

The subjects in this study were seven male cosmonauts who participated in Space Station «MIR» missions («MIR» missions EP 18, 22, 24 26, 27). Prior to the flight, their average age, height, body mass were  $45.1 \pm 2.0$  years (range 43-54),  $176.0 \pm 2.3$  cm (range 167-182),  $79.9 \pm 2.0$  kg (range 70-86), respectively (Table 1). The duration of the space flight was by mean  $213.0 \pm 30.5$  days (range 115-380). Each subject performed two sets of experiments 30 days before space flight (baseline data collections) and immediately after space flight (return) of 3 days.

### *Familiarization*

The cosmonauts reported to the laboratory twice. During the first visit, the cosmonauts were familiarized with the experimental set-up and

procedures. The cosmonauts gave their written informed consent to participate in this study. On a subsequent day, the cosmonauts were involved in testing contraction properties of the ankle extensor muscles. Each subject served as his own control.

## Testing procedure and measurement

### Isometric set-up

The mechanical responses of the TS muscle were recorded by method tendometry (59) (Fig. 1, *top panel, left*) which made it possible to measure the force of a single muscle contraction by the degree of tension change in muscle distal tendon (44, 46-48). Measurement of muscle tension using a strain-gauge transducer is based on the physical law of the resolution of forces according to the parallelogram principle (Fig 1, *top panel, insert*). If a strain-gauge transducer is pressed to the tendon, the transducer causes it to bend at an angle. The force ( $F_1$ ) that is directed along the muscle axis to the proximal point of attaching and originates during the muscle contraction is oppositely directed and equal to the force ( $F_2$ ) that is directed to the distal point of the tendon attachment.  $F_1$  which is directed across the tendon, operates at the point of the transducer and tendon contraction. If the angle at which the tendon bends is constant, the force ( $F$ ) recorded by the strain-gauge dynamometer is proportional to  $F_1$  (or  $F_2$ ). A rigid

using a strain-gauge transducer, because any deformation under tendon pressure will change the transducer position and alter the tendon angle. A steel dynamometer ring was used in our transducer.

The subject was seated comfortably on a special chair in a standard position (knee joint angle between tibia and sole of foot of  $\sim 90$  deg). The position of the seat was adjusted to the individual and then firmly secured. A rigid leg fixation provided the isometric regimen of the muscle contraction. The dynamometer that is a steel ring with a saddle-shaped special block was tightly attached to support the Achilles tendon of the muscle. The degree of pressure between the tendometrical sensor and the tendon was constant for all the subjects and amounted to 5 kg.

### Surface electromyography

After careful preparation of the skin including shaving excess hair, abrading the skin with fine sandpaper, and cleaning the skin with an isopropyl alcohol swab to reduce impedance below 5 k $\Omega$ , pairs of surface Ag-AgCl electrodes ( $\square$  8 mm, center to center distance 25 mm and a recording area of 50 mm<sup>2</sup>), were placed over the muscle bellies of medial (MG) and lateral (LG) gastrocnemius, and soleus (Sol) muscles. The electrodes were placed longitudinally with respect to the underlying muscle fiber arrangement and located

Table 1 Physical characteristics ( $M \pm m$ ,  $n = 7$ ) of the permanent crewmembers of space mission

Age, (years)	Height, (cm)	Body mass, (kg)	Duration space, (day/hour/min)
54	167	79.3	115/08/43
40	182	83.0	196/16/31
50	174	86.0	379/14/51
43	182	81.0	196/17/26
40	175	83.0	196/17/26
47	170	77.0	207/12/02
42	182	70.0	188/20/16
<b>45.1 <math>\pm</math> 2.0</b>	<b>176.0 <math>\pm</math> 2.3</b>	<b>79.9 <math>\pm</math> 2.0</b>	<b>213.0 <math>\pm</math> 30.5</b>

dynamometer is needed for recording the muscle force

according to the recommendations by SENIAM (surface

EMG for noninvasive assessment of muscles). For the soleus muscle, electrodes were attached to the skin over the middle part of the soleus muscle, belly and placed ~ 6 cm distally of the stimulation electrodes. The large grounding electrode (7.5 cm x 6.5 cm) was located on the proximal portion of the leg between the upper recording electrode and the stimulating electrodes. Recordings of the electrical responses (EMG) of the skeletal muscle during slow MVC were made during for a short period (~ 0.2 s). EMG signals were amplified (x 1,000) and digitized (bandwidth of 0–2,000 Hz) at a sampling rate of 5 kΩ. During contraction the EMG signal was recorded on FM tape and simultaneously displayed on an oscilloscope to assess its quality. EMG signals were bandpass filtered between 20 and 500 Hz, and smoothed using a moving root-mean-square filter with a time constant of 50 ms.

### **Electrical stimulation**

A single, square-wave, supramaximal transcutaneous electrical stimulus of 1 ms duration was delivered to the *n. tibial*. Transcutaneous electrical stimuli were delivered to the tibial nerve using a high-voltage (maximal voltage = 400 V), constant current stimulator (model «ESU-1», USSR). The cathode (active electrode) was a metal probe (□ 1 cm) with the tip covered in a saline-soaked sponge, which was pressed over the tibial nerve in the popliteal fossa which is the place of the lowest resistance. The anode (passive electrode) was a 6 x 4 cm rectangular self-adhesive electrode that was positioned between the tibial tuberosity and the patella. The large grounding electrode (7.5 cm x 6.5 cm) was located in the proximal portion of the leg between the peak-up and stimulating electrodes. Single stimuli were administered to the tibial nerve at a low current (amperage = 20 mA) to determine the optimal probe location based on the visual inspection of the compound muscle action potential (M-wave) and H-reflex of the soleus muscle that were monitored on an cathode-ray storage tube oscilloscope. A single stimulus was given every 30 s. Once the location was determined and marked, the maximal M-wave was achieved with incremental (5 mA) amperage increases until a plateau in the peak-to-peak M-wave was observed after three successive amperage increases. To assure a supramaximal stimulus, 120 % of the stimulus that elicited the maximal M-wave was used

during the evoked twitch procedures.

The isometric tetanic contractions of the TS muscle were induced by electrical stimulation of the *n. tibial* using supramaximal rectangular pulses with a frequency of 150 impulses·s<sup>-1</sup> (52). All the recordings were made in a room at constant temperature (~ 22 ± 1 C).

The contractile properties of the TS muscle were tested twice: pre- (~ 30-days) and post-space flight (~ 3-4-days) and the test protocol were identical for both pre mission and post mission tests.

### ***Tension properties***

The whole protocol was executed by one investigator. For all cosmonauts, the right leg was studied. The contractile properties of the TS muscle were estimated according to the mechanical parameters of a voluntary and electrically evoked contraction (maximal isometric twitch and tetanic contractions, double stimulation).

### ***Voluntary contraction.***

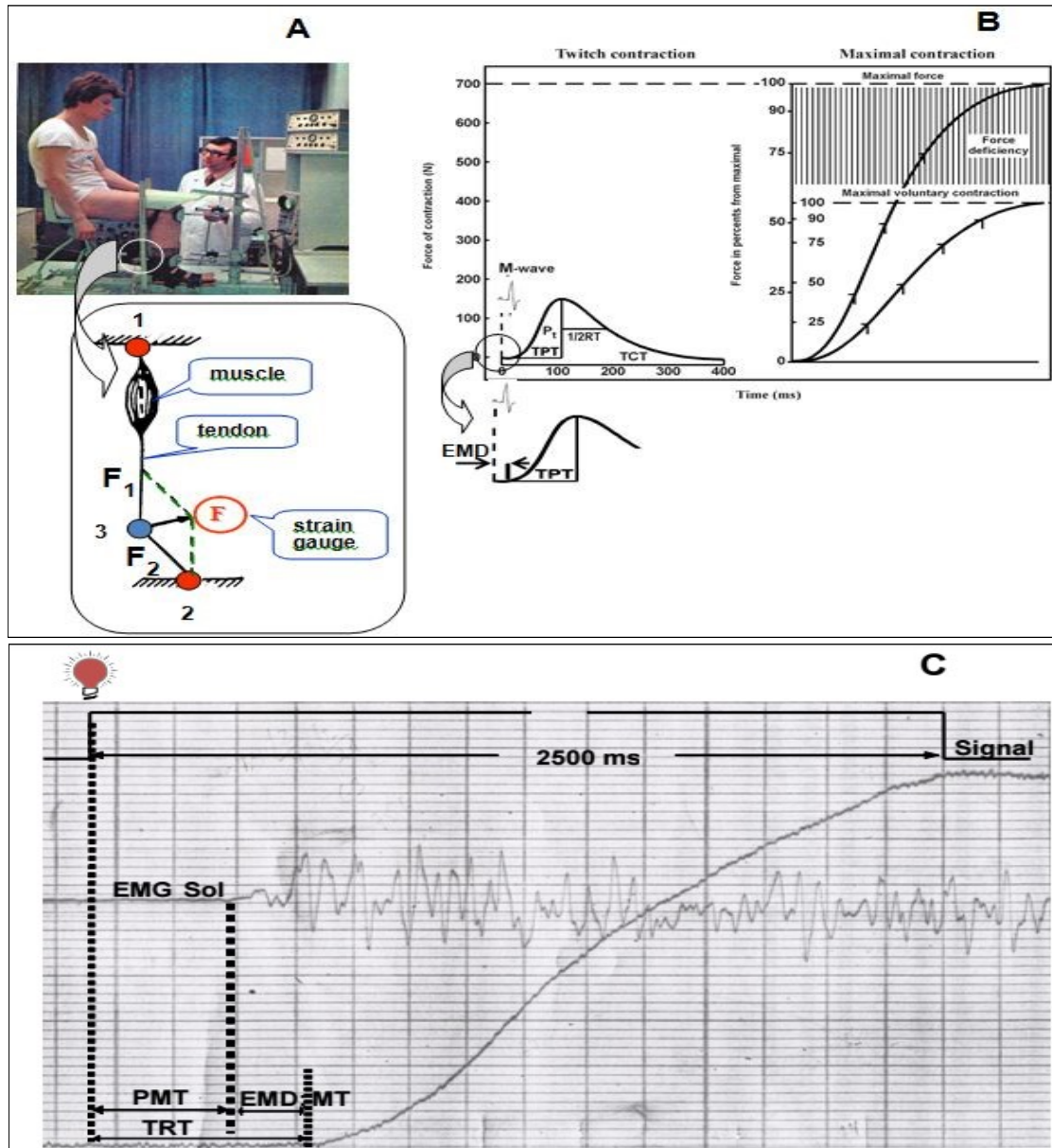
The maximal voluntary contraction was measured from the tendogram of an isometric voluntary contraction performed, on instruction, «*to exert a maximal contraction*» (Fig. 1, top panel, right). Maximal voluntary contraction was determined during three contractions of 3-4 s duration separated by 3 min. The largest of three contractions was considered as the maximal voluntary contraction (MVC). During the contractions, the subjects were verbally encouraged and a visual feedback was provided.

### ***Evoked (tetanic) contraction***

The maximal strength was measured from the tendogram from the evoked contraction ( $P_o$ , Fig. 1, top panel, right.) in response to an electric tetanic stimulation of the nerve, innervating the TS muscle, with a frequency of 150 impulses·s<sup>-1</sup> (43, 44).

The difference between  $P_o$  and MVC expressed as a percentage of the  $P_o$  value and referred to as force deficit ( $P_d$ ) has also been calculated (43, 44) (Fig. 1, top panel, right).





**Fig. 1. Experimental set-up and scheme estimated of parameters**

**A.** Experimental set-up and scheme the principle of tendometry method: **B.** Examples measurements of mechanical response parameters in isometric twitch contraction curve (*left*) and in electrically evoked tetanic tension and voluntary muscle tension development (*right*), and measurements electromechanical delay (*insert*) TPT, a time-to-peak;  $1/2RT$ , a half-relaxation time; TCT, a total contraction time;  $P_t$ , a twitch force; EMD, a electromechanical delay.

**C.** Schematic presentation of a sample contraction showing total reaction time (TRT) with its premotor (PMT) and motor (MT) components, force-time curve and EMG recorded from m. soleus.

### Evoked (double) contraction

Duration of an active state plateau of the contractile components of muscle fibers of the TS muscle was measured using the method of interval between stimuli. Supramaximal twin stimuli at 330, 250, 200, 100, 50, and 20 Hz were applied (46). The maximal strength (amplitude) of the muscle contraction was determined and expressed as a percentage of the twitch contraction.

### **Velocity properties**

The maximal isometric peak twitch force ( $P_t$ ) was measured from the tendogram of the TS muscle isometric twitch response to a single electrical stimulus applied to the tibial nerve. The time from the moment of stimulation to peak twitch (TPT), the time from contraction peak to half-relaxation ( $1/2$  RT) and total contraction time (TCT) - the time from moment of stimulation to the total muscle relaxation - were calculated from the tendogram of the isometric twitch (Fig. 1, top panel, right).

### **Rate of force development**

The rate of development of increased muscle tension was calculated from the tendogram by the isometric voluntary contraction after the instruction «to exert the fastest and greatest tension» using a relative scale, i.e. the time of reaching 25, 50, 75, 90 % of maximum tension (36, 37, 43, 44). Similarly, the rate of rise of the evoked contraction, in response to electrical stimulation of the n. tibial with a frequency of 150 impulses  $\square$  s<sup>-1</sup> (43, 44) (Fig. 1, top panel, right). The maximum rates of voluntary contraction ( $dP_v/dt$ ), and evoked contraction ( $dP_{ec}/dt$ ) development were obtained by differentiation of the analog signal.

### **Electromechanical delay**

Electromechanical delay (EMD) comprises an important portion of the rate of tension development phase of the contraction (28), where changes in motor unit activity patterns have been demonstrated to play a critical role in the maximal rate of force development (84).

The experiments were divided into two protocols.

### Protocol 1 $\square$ Voluntary contraction

On a light signal the subject carried out plantar flexor under condition of «to contract as it is possible quickly and strongly» (Fig. 1, bottom panel). Voluntary contraction in response to a visual stimulus (flash lamp) was adopted as a rapid ballistic movement. The signal to movement of «explosive» character was the visual diode – lamp ( $\varnothing$  7 mm, 1 W)  $\square$  was placed at eye level 1 m in front of the subject. Lasted signals were 2.5 s and the pause between the signals was random ranging from 1.4 to 5.0 s. The threshold for force was 5 N.

A separate timer was used to record the time interval from the presentation of the light signal to movement. The special timer allowing synchronously with presentation of a light signal to the beginning of movement to carry out record of development of mechanical answer the human TS muscle was used.

From the tendogram estimated total reaction time (TRT), defined as the time interval from the application of the light stimulus to movement. TPT was divided into pre-motor (PMT), defined as the time interval from the application of the stimulus to the change in electrical activity of the soleus muscle. EMD or motor time (MT) was determined from the time lag between the onset of dorsiflexion force and surface EMG in the soleus muscle (84). Surface EMG onset threshold was identified as the first point of the surface EMG signal to rise above the 95 % confidence interval for baseline noise and to remain above the 95 % confidence interval for 20 ms (22). The force thresholds were also taken as relative values of 2 % from the maximum isometric force level of each contraction. The onset of EMG integration was initiated 70 ms before the identified onset of the force time curve, which accounts for EMD (8).

Subjects were permitted three practice trials separated by 30 s and in most cases the mean of three readings was used to determine TRT, PMT and EMD.

### Protocol 2 $\square$ Twitch contraction

To evaluate time of involuntary EMD, rectangular electrical pulses were applied to n. tibialis. The active electrode was placed over the popliteal space. Four single supramaximal stimuli were delivered to n. tibialis and a maximal M-wave recorded. The rest

interval between stimuli was no less than 30 s. The EMD was determined as a time interval between stimulation artifact and the onset of the twitch response (Fig. 1, *top panel, right, insert*).

The results of the experiment were simultaneously recorded on magnetic tape and simultaneously displayed on an oscilloscope to assess its quality.

### Exercise regimens

To preserve the muscle contractile properties in long-term space missions, cosmonauts used physical training (PT). Details of the training program and performance tests have been provided elsewhere (24, 76). PT which were mostly of a locomotor type and included a warm-up (walking on a treadmill for 5 min), and low (2 min), moderate (2 min) and maximum (1 min) intensity running. PT were performed for 1.5–2 hours. Four-day microcycles, each including 3 days with PT and 1 day of rest, were followed in the PT program (24, 76).

A treadmill and a cycle ergometer were the main PT tools, training the cardiovascular and respiratory systems (33). The treadmill device could be used in a passive (subject driven) or active (motorized) mode of operation, which was selected by the crewmember during each exercise session. Crewmembers used a subject-loading device to fix themselves to the treadmill, which provided varying levels of loading relative to body weight (typical load was ~ 70 % of body weight) during use. In this way, the crewmembers could complete running or walking exercise while partially loaded. The cycle ergometer provided a load of 50–225 W at a pedaling rate of 40–80 rpm. The crewmembers also had access to bungee cords, which they could use to provide resistance-type exercise for various muscle groups.

### Statistics

Conventional statistical methods were used for the calculation of means and standard errors ( $\pm$  SE). A Wilcoxon's signed-rank test for paired differences was used to test changes in all mechanical parameters due to space flight. Furthermore, differences between baseline (background) values of the subject and those post-space flight were tested for significance by

Student's paired  $t$  test. All data are expressed as means  $\pm$  standard error (SE) within the text and the tables and as means  $\pm$  SE in the figures for the sake of clarity. The percentage changes for pre- and post-space flight was also calculated.

For comparative change of contractile properties the TS muscle during long-term space flight and observable changes during long-term models simulating weightlessness – bed rest (Koryak 1995a; 1998) similar duration used calculated by  $((\text{before} - \text{after}) / \text{before}) \times 100 \%$ .

All statistical analyses were conducted at a level of significance of  $p < 0.05$ .

## III. RESULTS

### Tension properties

Mean data of the changes in the TS muscle tension properties are shown in Figure 2 (*top panel*). Isometric  $P_t$  increased by mean 14.8 % (pre  $106.0 \pm 7.8$  N compared to post  $121.6 \pm 17.6$  N) after space flight ( $p > 0.05$ ). MVC decreased by a mean of 41.7 % (pre  $520.0 \pm 66.7$  N compared to post  $303.1 \pm 50.0$  N;  $p < 0.05$ ), and isometric muscle tetanic ( $P_0$ ) decreased by a mean of 25.6 % (pre  $738.6 \pm 65.7$  N compared to post-space flights  $549.4 \pm 37.3$  N;  $p < 0.05$ ), after space flight, respectively. The  $P_d$  (Fig. 2, *top panel*) increased significantly by a mean of 49.7 % (pre  $32.2 \pm 4.6$  % compared to post-space flight  $46.7 \pm 5.4$  %;  $p < 0.01$ ).

A summary of individual values is given in Figure 2 (*middle panel*). Post-flight maximal isometric MVC in plantar flexion, collected near landing (immediately after space flight (return - R); R+3 days), indicated a decrease in MVC. More precisely, decreases in MVC were found for each cosmonaut from baseline data collections ranging from 22 % to 65 %, respectively). For the population MVC was found to be significantly higher in pre-flight condition than in post-flight condition ( $p < 0.05$ ).

Post-flight maximal isometric muscle tetanic ( $P_0$ ) in plantar flexion indicated a decrease in  $P_0$  (Fig. 2, *lower panel*). More precisely, decreases in  $P_0$  were found for each cosmonaut from baseline data collections (baseline data collections) ranging from 8 to



41 %, whereas 2 subjects (1, and 7, respectively) had had concerning smaller decrease  $P_o$  (8, and 11 %, respectively). For the population  $P_o$  was found to be significantly higher in pre-flight condition than in post-flight condition.

The analysis of the data shows, that there is no connection between basic value of force of reduction of a muscle and degree of drop force properties muscle after space flight. For example, cosmonauts 3 and 4, the highest parameters, having up to space flight, MVC, after space flight differ on depth of drop of force of reduction. There are no such connections and for a parameter  $P_o$  (Fig. 2).

Figure 3 shows a 55 % increase ( $p < 0.05$ ) of iEMG and a 71 % increase ( $p < 0.05$ ) of the iEMG/MVC ratio for a slow MVC after the space flight. The increase in both IEMG and iEMG/MVC are indicators of decreases in efficiency of the degree of electrical activation in the muscle after flight. The degree of activation required to generate a force is estimated by the EMG/force relation. The slope of the EMG/force relation was decrease significantly after space flight ( $p < 0.05$ ).

The mean changes in force of the TS muscle contraction during doublet stimulation, in which a second pulse was applied at various intervals, are presented graphically in Figure 3. The greatest force of contraction under these conditions was at an interval of between 4 and 10 ms and decrease or increase in the interval were accompanied by a considerable decline. The relative increase in force as a result of doublet stimulation was significantly lower after long-term space flight in comparison with the control (baseline data collections) value ( $p < 0.01-0.001$ ).

### Velocity properties

The data of the change of mean time of isometric twitch contraction as the opposite value to contraction velocity for the TS muscle after long-term space flight, is given in Figure 5. As is seen from the data analysis, exposure to microgravity conditions was accompanied by a statistically significant decrease of the muscle contraction and increased relaxation (1/2 RT) velocity. Thus, TPT increase by a mean of 7.7 % (pre  $130 \pm 2$  ms compared to post  $140 \pm 6$  ms;  $p < 0.05$ ) after space flight. 1/2 RT was shorter after space flight than in the control value. Thus, 1/2 RT reduced by a

mean of 20.6 % (pre  $97 \pm 4$  ms compared to post  $77 \pm 4$  ms;  $p < 0.05$ ), but TCT increase by a mean of 7.5 % (pre  $456 \pm 25$  ms compared to post  $490 \pm 31$  ms;  $p < 0.01$ ).

The same subjects showing increase in TPT also showed significant increase in the twitch-to-tetanic ratio by a mean of 46.7 % (pre  $0.15 \pm 0.01$  compared to post  $0.22 \pm 0.02$ ;  $p < 0.05$ ) (Table 2).

Individual data of each cosmonaut from baseline data collections and collected near landing (R +3) are summarized in Figure 5 (*middle and low panel*). Post-flight TPT, collected near landing, indicated a increased in TPT. More precisely, increases in TPT were found for 5 subjects ranging from 8 to 24 %, whereas 2 subjects (3, and 4, respectively) had slightly decreased TPT (6, and 12 %, respectively).

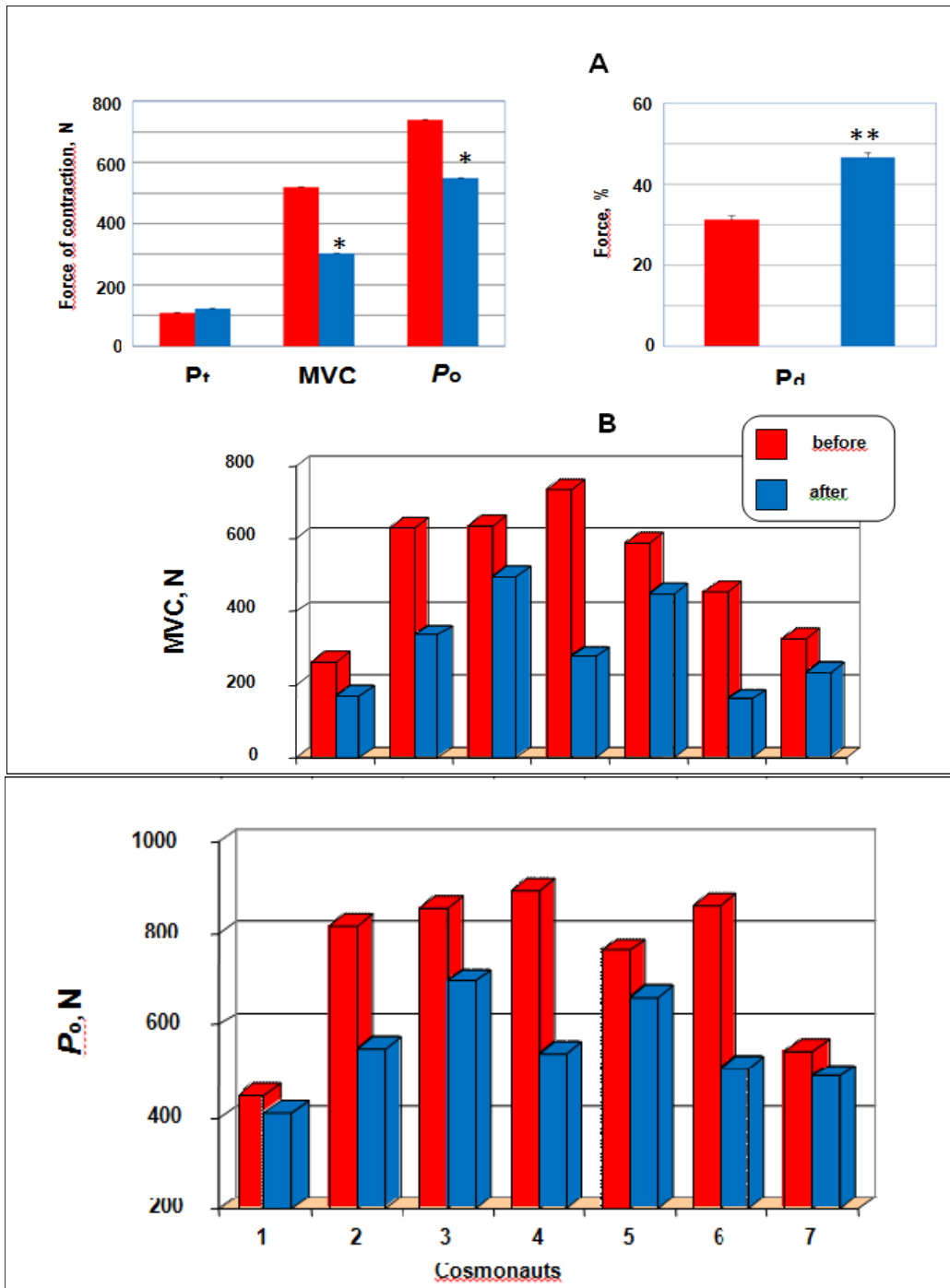
On the other hand, the effect of exposure to microgravity on relaxation (1/2 RT) velocity was tested by comparing 1/2 RT values in pre-flight and post-flight conditions. Seven cosmonauts presented an increase in 1/2 RT ranging made an interval 2 % to 37 %, whereas the one subjects (cosmonaut 5) had slightly decreased 1/2 RT (2 %). Statistical analysis, taking each subject into account, revealed that the decrease in 1/2 RT was significant for the whole population. Individual data are summarized in Figure 5.

### Rate of force development

Mean changes in the rate of development of isometric tension of the TS muscle are given in Figure 6. The decrease in the MVC (42 %) was associated with a significant slowing of the rate of tension development during a voluntary isometric contraction (Fig. 6, *left curve*;  $p < 0.01-0.001$ ); maximal  $dP_{ec}/dt$  significant decrease by a mean of 36.2 % when normalized as the percentage MVC (Fig. 6, *insert*;  $p < 0.001$ ).

Analysis of the *force-time* curve of the electrically evoked contractions did not reveal significant differences (Fig. 6, *right curve*;  $p > 0.05$ ) while the maximal  $dP_{ec}/dt$  was significant increased by a mean of 43.7 % after space flights (Fig. 6, *insert*;  $p < 0.001$ ). These mechanical dissociations suggested that some state beyond the membrane processes was changed.

### Electromechanical delay



**Fig. 2. The effects of long-term space flights on strength properties**

**A.** The maximal twitch response of force ( $P_t$ ), maximal voluntary contraction (MVC), maximal electrically evoked tetanic contraction ( $P_o$ , recorded at  $150 \text{ impulses}\cdot\text{s}^{-1}$ ) (left panel), and force deficit ( $P_d$ ), before and after prolonged space flights (right panel). **B.** The histograms represent the individual MVC (top panel) and  $P_o$  (bottom panel) values of each cosmonaut from baseline data collections and 3 days after return test. All values are means  $\pm$  SE. Significantly different between groups for corresponding contractions: \*\* $p < 0.05$  \*\*\* $p < 0.01$

The mean changes in EMD under space flight are shown in Table 2. The EMD increased significantly, by  $34.1 \pm 1.3$  % after space flight (pre  $31.4 \pm 2.8$  ms compared to post  $42.1 \pm 3.4$  ms;  $p < 0.05$ ).

The PMT decreased significantly by a mean of 18.8 % (pre  $256.4 \pm 24.1$  ms compared to post  $207.6 \pm 19.6$  ms;  $p < 0.01$ ), and TRT decreased by a mean of 14.1 % (pre  $289.1 \pm 25.0$  ms compared to post  $248.4 \pm 20.5$  ms;  $p < 0.01$ ) after space flight.

The coefficients of correlation between the EMD and MVC before space flight were  $-0.67$  ( $p < 0.05$ ) and strongest correlations were found between EMD and ballistic voluntary force ( $r = 0.90$ ;  $p < 0.01$ ). The coefficients of correlation decreased between the EMD and MVC after space flight ( $r = -0.57$ ;  $p = 0.05$ ), and between the EMD and ballistic voluntary force ( $r = -0.70$ ;  $p = 0.07$ ).

EMD during evoked contraction did not differ significantly before and after space flight (Table 2).

Comparison of EMD during evoked and voluntary contractions revealed a longer EMD during voluntary both pre- and post-space flight. For instance, pre-space flight value EMD during voluntary contractions were by a mean of  $31.4 \pm 3.1$  ms in contrast to  $10.3 \pm 0.4$  ms during evoked contractions ( $p < 0.05$ ); post-flight values were by a mean of  $42.1 \pm 3.1$  ms and  $12.43 \pm 0.3$  ms, respectively (Table 2).

### Comparison of space flight to a period of bed-rest

In previous work, we examined the responses of the human TS muscle to 120 days of complete bed-rest (44). Figure 7 compares the results from this previous work to the present study. Inter-subject variability appears to be similar for each model. These data indicated no differences in the relative changes between the two models for MVC, and  $R_t$  and  $P_o$ , and force deficit, TPT and 1/2 RT. On the other hand, our data demonstrate that the countermeasures employed during space flights have not been completely successful in preventing reductions in alterations in neuromuscular performance. A better understanding of how humans respond to space flight is a requirement for the development of more effective countermeasures.

### DISCUSSION

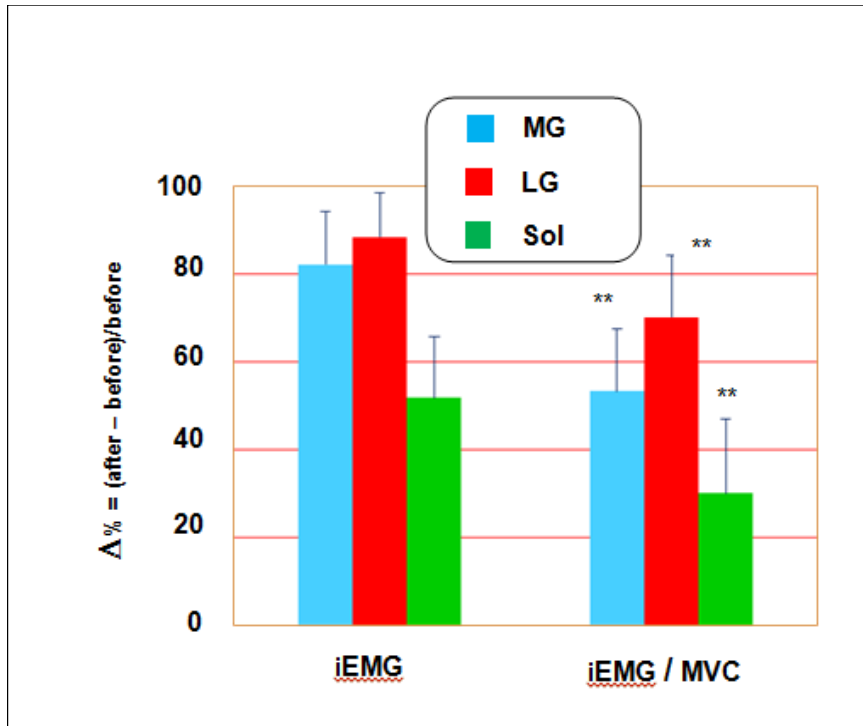
The major aim of the present study was to

examine the influence of prolonged microgravity (weightlessness) on the contractile responses of skeletal muscle in intact healthy men. Muscle to experimental conditions may occur for a number of reasons and whether the changes in contractile processes or whether the neural (motor) command (43, 73). The results of the study revealed the change in the TS muscle contractile properties after long-term exposure to space flight. The adaptation of muscle contraction to the effect of long-term weightlessness may be the result of changes which occur within the nervous command of muscle contraction or at peripheral sites.

The use of electrically evoked twitch and maximal tetanic contractions is well established in the study of human contractile function. The results of this study demonstrate that contractile properties of skeletal muscle are altered during typical long-term space flights (a more than 4 months) on aboard the Space Station «MIR». Experiments utilizing fixed end, unloading, isometric contractions revealed alterations in force production, velocity and force-velocity output of post-flight muscle. Presumably these alterations result from the lack of normal weight-bearing activity by the lower limb postural muscles in reduced gravity conditions aboard the Space Station.

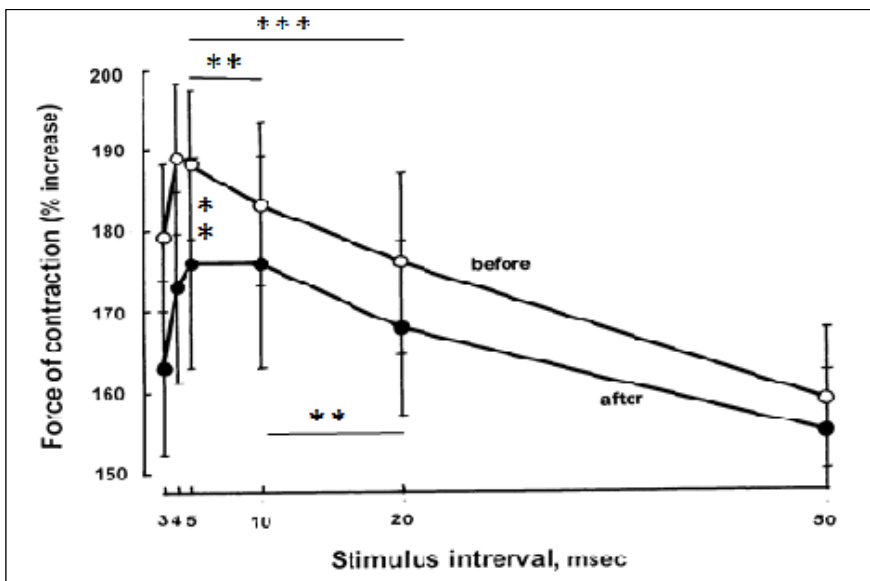
### Effects of space flight on force properties

We anticipated that the changes in isometric  $P_t$  would correspond to those in MVC, namely a decrease with microgravity. In contrast, we observed a nonsignificant increase in  $P_t$  after long-term space flights. These unexpected findings are not unique. Edgerton et al. (20) found a nonsignificant increase in  $P_t$  after 6 mo hindlimb immobilized skeletal muscles of a nonhuman primate (*Galago senegalensis*), and Koryak (45, 46) after 7 days 'dry' water immersion in the human TS muscle. These changes are quite similar to these observed in our study. These changes in twitch tension may reflect alterations in stiffness (extensibility) in human muscles. A decrease in muscle extensibility (stiffness), which has been observed after disuse/space flight (30, 62) would be the changes in isometric  $P_t$ . In contrast,  $P_o$  decreased after space flight. Thus there is a tendency for the twitch-to-tetanus ratio to increase after space flight. These changes in the twitch-to-tetanus ratio may reflect alterations in muscle extensibility. We



**Fig. 3. The effects of long-term space flights on EMG activities**

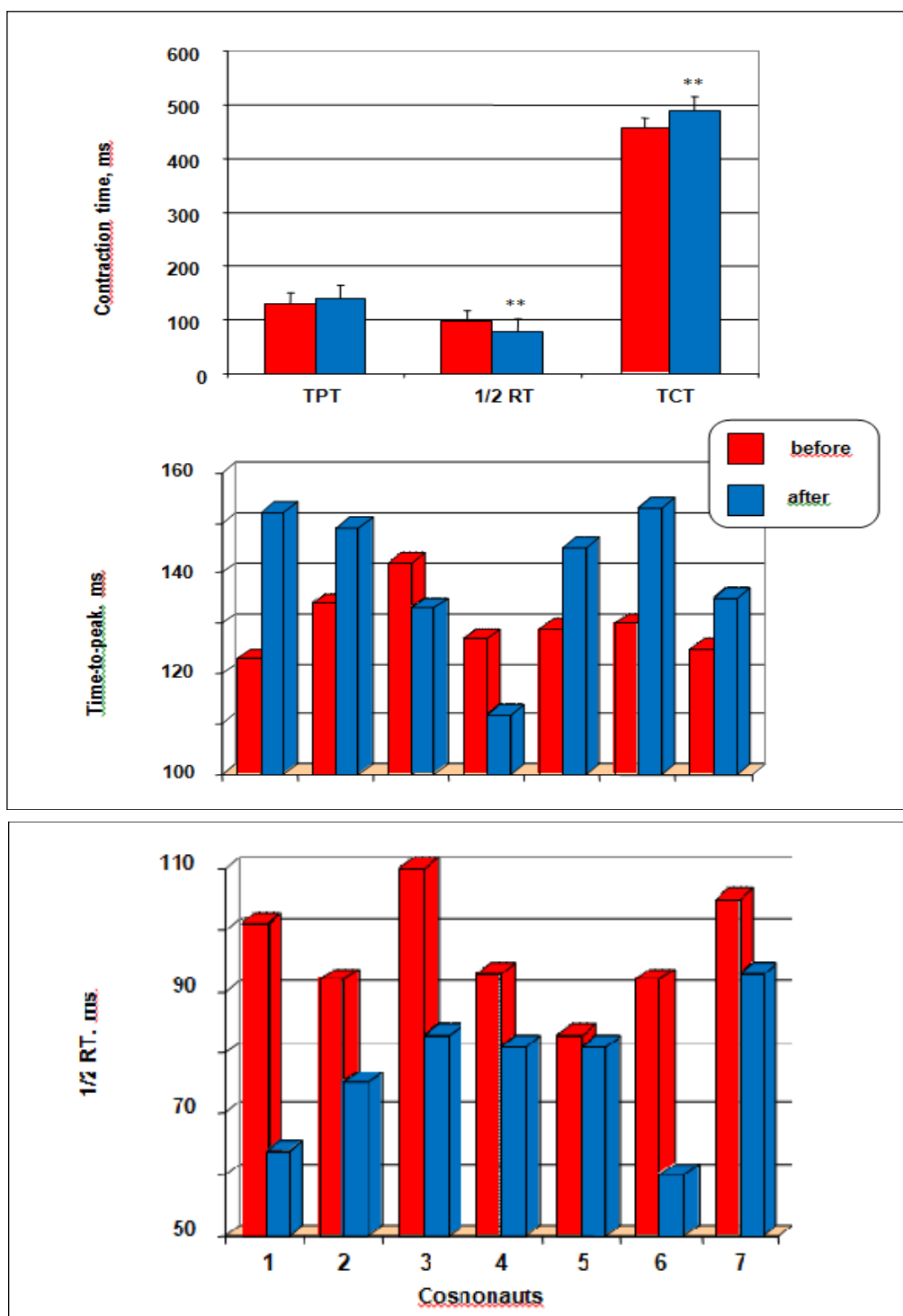
Activation of the medial and lateral gastrocnemius and soleus muscles during MVC after long-term space flight. Values are expressed as percentage of control (before). All values are means  $\pm$  SE. Significantly different between groups for corresponding contractions: \*\*p < 0.05.



**Fig. 4. The effects of long-term space flights on maximal electrically evoked contraction with double stimulation**

Mean value of the maximal force of contraction of the triceps surae muscle with doublet stimulation at different intervals between impulses. All values are means  $\pm$  SE. Significantly different between groups for corresponding contractions: \*\*p < 0.05 \*\*\*p < 0.01.





**Fig. 5. The effects of long-term space flights on velocity properties**

Time-to-peak twitch (TPT), and time to half-relaxation (1/2 RT), and total contraction time (TCT) before and after prolonged space flights (*top panel*), and the histograms represent the individual TPT (*middle panel*), and made an interval 1/2RT (*bottom panel*) values of each cosmonaut from baseline data collections and 3 days after return test. All values are means  $\pm$  SE. Significantly different between groups for corresponding contractions:  $**p < 0.05$

speculate that in our experiment, space flight is the cause of a decrease in muscle extensibility.

After prolonged space flights the electrically evoked contractions ( $P_0$ ) decreased significantly at a rate of 26 % of normal. The  $P_0$  is a direct measure of the force-generating capacity of a muscle and has been considered to reflect the number of active interactions between actin and myosin (17). Disuse produced a decline in  $P_0$  (21, 45, 46). This

bridge could have been decreased. However, according to Steven et al. (77) have shown that when it was expressed per cross-sectional area, the force was unchanged after disuse. This would indicate that the first hypothesis of a decrease in the maximal number of cross-bridges was more appropriate to our results, rather than a change in density.

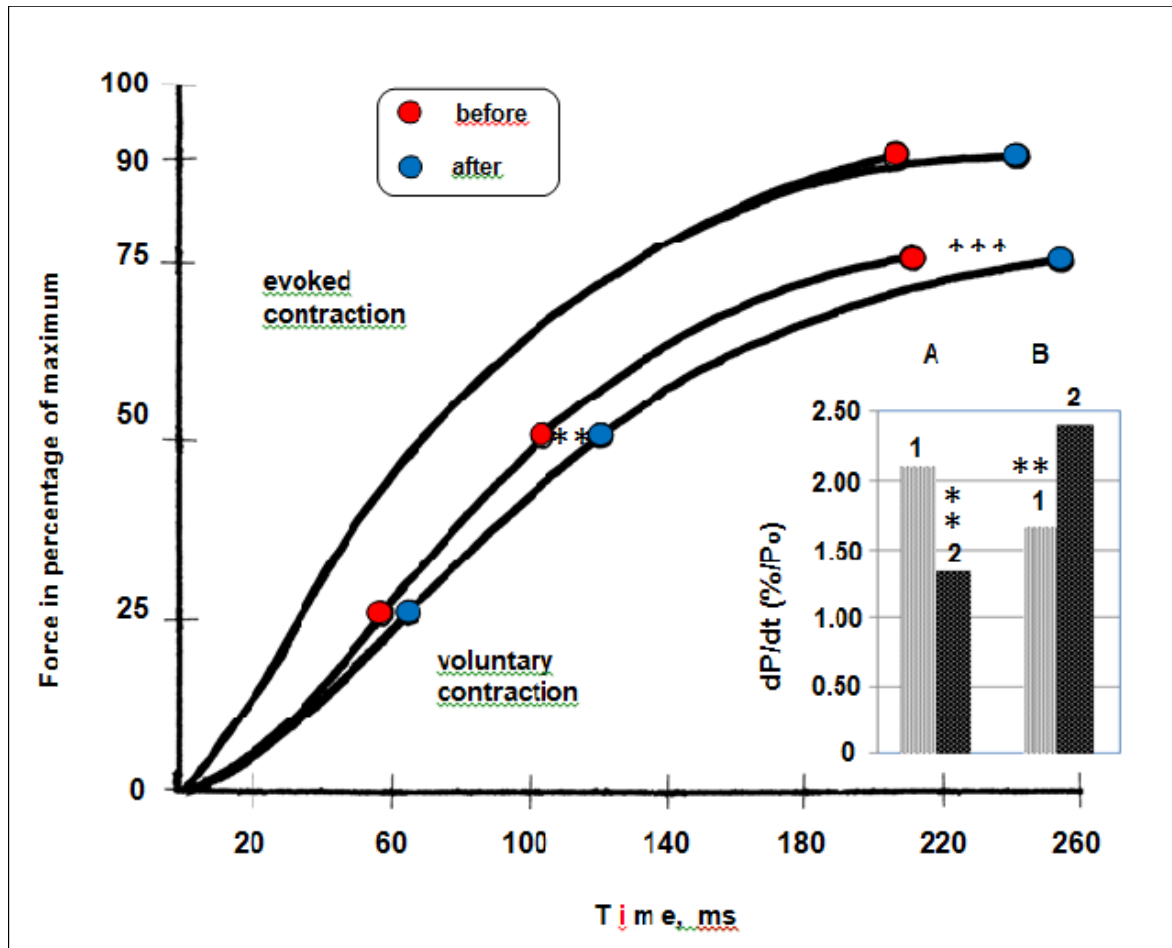
As a whole the mechanisms responsible for the force loss with microgravity are not well

Table 2 The mechanical and time characteristics of the human triceps surae muscle after a long-duration space flight ( $M \pm m, n = 7$ )

	Before	After	$\Delta, \%$
$MVC_{slow}, N$	$519.9 \pm 66.7$	$303.1 \pm 50.0$	41.7
$MVC_{fast}, N$	$467.9 \pm 40.2$	$403.2 \pm 43.2$	13.8
$0,5 MVC_{fast}/t_{0,5}, N/ms$	$1.422 \pm 1,373$	$1.756 \pm 1,67$	23.4
$dP_{vc}/dt, \%/ms$	$20.60 \pm 0$	$13.14 \pm 0$	36.2
Twitch-to-tetanic ratio	$0.15 \pm 0.01$	$0.22 \pm 0.02$	46.7
PMT, ms	$256 \pm 24$	$208 \pm 20$	18.8
EMD, ms	$31.4 \pm 2.8$	$42.1 \pm 3.4$	34.1
$P_t, N$	$105.9 \pm 7.8$	$12.4 \pm 1.8$	14.8
$dP_t/dt, \%/ms$	$13.1 \pm 0.29$	$1.19 \pm 0.02$	11.2
$EMD_t, ms$	$10.3 \pm 0.4$	$12.4 \pm 0.3$	20.4
$P_0, N$	$738.7 \pm 65.7$	$549.4 \pm 37.3$	14.8
$dP_{ec}/dt, \%/ms$	$16.38 \pm 0$	$23.54 \pm 0$	43.7

decline could reflect a decrease in the number of active cross-bridges and be expected to decrease the work capacity. Two hypothesis may be suggested to account for the observation. First, the total number of cross-bridges could have been smaller after the period of space flight. Second, the force output per cross-

understood. However, changes in the force might have been caused by changes in different architectural properties, such as muscle length, and fascicle length, and pennation angles (27, 85). Consequently, the relationships among joint angles, muscle lengths, and pennation angles are highly specific to muscle. Muscle



**Fig. 6.** The effects of long-term space flights on development of force of the triceps surae muscle expressed relative to the maximal force (*left*) and the maximal rate of rise of tension development (*right*)

Average curves showing the development of force while executing explosive voluntary contraction and as a result of electrical stimulation at  $150 \text{ impulses} \times \text{s}^{-1}$ . Significantly different between groups for corresponding contractions:  $**p < 0.05$   $***p < 0.01$

architecture, together with intrinsic properties such as also fiber composition, also affects functional characteristics of muscle, e.g., maximal shortening velocity and  $P_0$  (70). In addition, considering that of the TS muscle our experimental environment was not extended and tensed, which makes possible the associated of such a condition with physiological shortening, it may be assumed that the total number of successively connected sarcomeres was considerably decreased (25). These may have contributed to the reduced in muscle layer thickness and fascicle angles. In fact, according to Clément et al. (16) it seems that cosmonauts adopt a dorsiflexion position during space flights. Then, in postflight, a shortening of the plantar flexors will occur when the preflight neutral position is reached.

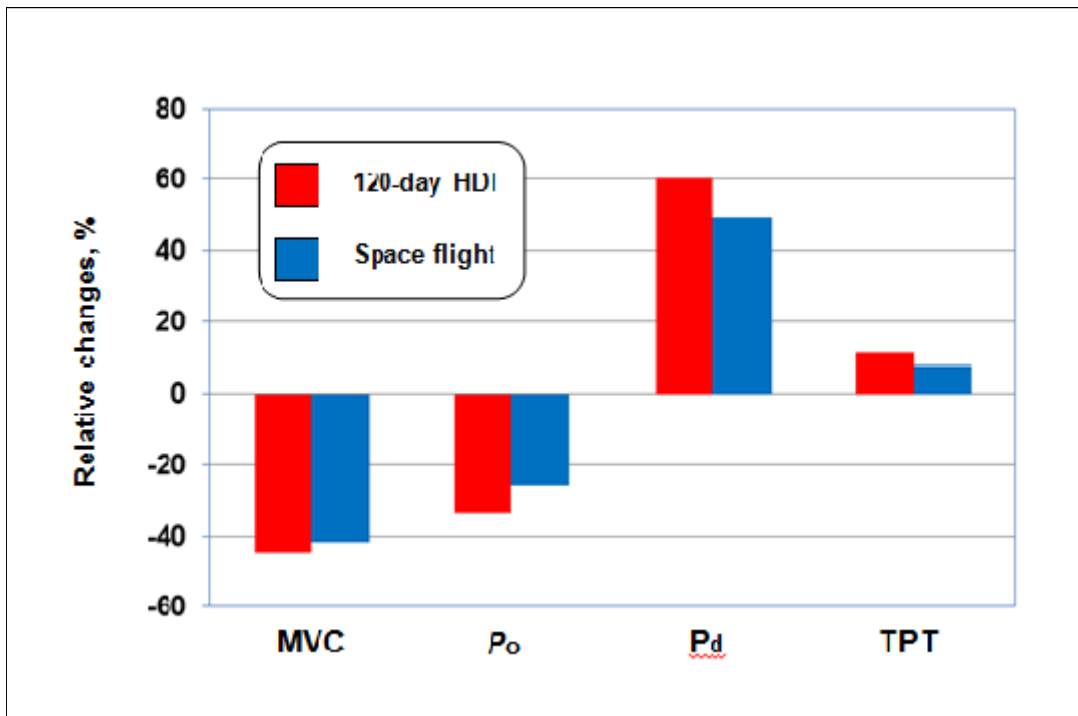
The measurement of MVC depends on many factors, such as motivation of the cosmonauts to give their maximal effort. MVC values obtained in pre-flight conditions correspond to the data report in the literature (4, 57, 89). As found by other teams who also worked on the Space Station «MIR» mission (5, 89), our post-flight data indicated for each subject a significant decrease in MVC. For instance, Zange et al. (89), by means of a NMR technique, reported a reduction in muscle mass of the lower limbs of  $\sim 11\%$  and attributed these morphological data to a decrease in muscle cross-sectional area. Our post-flight data indicated for each subject a significant decrease in MVC. The larger fall in MVC in the present study could also be due to the effects of weightlessness on i) the intrinsic characteristics of the recruited motor units and ii) changes in the motor unit recruitment pattern. Such alterations have already been hypothesized by some authors. Additionally, a decline in strength was also proved by Lambert et al. (62) after a space flight on root mean square values, used for expressing the power of an EMG signal. These studies indicate decrease in normalized mean square values after space flights support this proposition that microgravity interferes substantially with the normal neural drive.

The much larger reduction in MVC (mean decrease 42 %) when compared with to changes in  $P_0$  after a prolonged space flights of 3 mo on Space Station «MIR» (mean decrease 24 %) may indicate an inability of the central nervous system to activate the TS muscle

normally. Whether this was due to a lack of motivation on the part of the subjects, or to an involuntary reduction in neural drive, is difficult to distinguish. Additionally, a decline in maximal power was also proved by Antonutto et al. (5) after 180 days space flight and was attributed to a decrease in neural input. The subjects certainly appeared well motivated and had no discomfort or knee stiffness before performing the test which could have account for the low MVC. The increase in force deficit would suggests a decline in central drive in the control of voluntary muscle by the motor nervous system. In fact, during MVC, the EMG activity has been found to be significantly changed by the inactivity itself (21, 48, 73). Moreover, observation of amplitude changes after inactivity has suggested that fewer motor unit were activated in disused muscle (73), and maximal firing frequency of motor unit has been found to be decreased (21). In fact, this decrease in maximal firing rate should imply the recruitment of a larger number of motor units to develop the same target strength in pre-flight and post-flight conditions.

On the other hand, a decrease in maximal firing rate could be explained by changes in proprioceptive afferents on the motoneurons (64). This suggests that in future studies in human cognizance must be taken of the initial physiological states of the muscle that are to be disused to access the extent to which neural and muscle function is affected by loss of voluntary movement. Additionally, the data of Antonutto et al. (4, 5) suggest that microgravity causes a fundamental alteration in motor control. They observed two-legged muscle power to decline considerably more than could be explained by the loss in muscle mass. Moreover, the loss of explosive leg power was associated with a substantial reduction in the EMG activity of the muscle. The data of Recktenwald et al. (71) also suggest that microgravity induced a reorganization of motor recruitment motor units. These changes of motor control, may be one contributing factor of microgravity to the reduced extensor muscle torque and maximal power previously experienced by cosmonauts/astronauts after space flight (5, 34) and be change in architecture as muscle fibers, and in a muscle-tendon complex, as previously is shown on astronauts after space flight (53) and after stay in head-down tilt bed-rest (41, 60).





**Fig. 7. Effects of 120 days of space flight and ground-based bed rest on the functional properties of the triceps surae muscle**

The bars represent the mean relative change experienced by cosmonaut and bed rest subjects. Bed rest data obtained from Koryak (44).

During bed-rest, subjects underwent the exact same physiological testing performed by the cosmonauts during this flight. Mechanical responses the TS muscle were obtained and analysed using identical procedures. By directly comparing the results from these two studies we have attempted to assess the validity of the ground-based, head-down tilt bed rest procedure as a model of human space flight. The reductions in both MVC and  $P_0$  did not vary by more than a few per cent between space flight and bed rest model. Thus, the results of this comparison indicate that in general, mechanisms of force production in TS muscle respond in a similar manner to either bed rest or space flight. We should point out that one difference between the bed rest and space flight studies was that the cosmonauts were required by «MIR» flight surgeons to perform aerobic countermeasure exercise during the flight. It is impossible to evaluate how this may have affected the comparison between bed rest and space flight. We would concur with that conclusion based on the similarities between the bed rest where subjects did not perform exercise countermeasures and space flight results. We studied contractile properties the TS muscle obtained from adult subjects before and after 120 days head down tilt bed rest (44, 47, 49). During bed rest subjects did perform exercise countermeasures. Training had caused a decrease of 3 % in MVC, and  $P_t$ , and in  $P_0$  of 14 %, and of 9 %, respectively. The force deficit had decreased significantly by 10 %. These experimental findings indicated that neural as well as muscle adaptation occurred in response to head-down tilt with countermeasures.

### Effects of space flight on velocity properties

The results showed that a slow contracting muscle group (43, 82) was affected by microgravity. These data extend previous finding concerning the effects of short-term voluntary 'dry' water immersion (45), and long-term bed-rest (44, 47) on the mechanical characteristics of the TS muscle. The functional components of the twitch duration are the TPT and the 1/2 RT. Significant increases in maximal isometric twitch TPT and decreased 1/2 RT were maintained during a 120-day bed-rest. In the present study, the difference between the post-flight and pre-flight TS muscles was ~ 8 %. The underlying mechanistic basis of TPT and 1/2 RT involves the competitive interaction of factors

involved with activation ( $\text{Ca}^{2+}$  release kinetics), cross-bridge cycling,  $\text{Ca}^{2+}$  uptake by the sarcoplasmic reticulum (SR), and changes the active fraction (muscle fibers) or the passive fraction (tendons) of the series-elastic component.

A likely explanation of the change in TPT in the real microgravity limbs is a relatively greater atrophy of type I fibres, which has been found to make up the majority of the TS muscle (40). However, since microgravity produces muscle atrophy both in fast and slow skeletal muscles and, in addition, have been shown to cause fibre type-specific changes in the contractile properties (29), other factor(s) may be affected that alter fibre type composition. Additionally, it is tempting to suggest that the decreased 1/2 RT of the space flight TS muscles is probably due to an increased number of fast SR  $\text{Ca}^{2+}$ -ATP-ase pumps, as observed in previous hindlimb-suspension studies (77).

One additional effect to consider is the fibre type distribution. Is shown, that after space flight percentage of fibers no significantly changed. Observed a small increase in the percentage of fast type IIa fibres post-space flight (86). In this connection it would be possible to expect augmentation of increase the rate of rise of evoked twitch contraction a muscle. However, as show our data time-to-peak of a muscle after flight is increased. With these data are compounded and earlier received data in simulated conditions (46, 48-51).

The rapid nature of the isometric changes, i.e., twitch duration, may be related to alterations in SR function (11, 26). The primary factor (mechanism) of the explanation for these the changes may be a reduction in the rate at which  $\text{Ca}^{2+}$  is dissociated from the myofibrillar proteins (9). Dissociation would occur more slowly if the rate of  $\text{Ca}^{2+}$  re-uptake by the SR was decreased. Such a decrease has been found following disuse (34). A reduced rate of  $\text{Ca}^{2+}$  dissociation from myofibrillar proteins might be expected due not only to increase the time course of the twitch response but also allow more force to be generated, since cross-bridges will continue to be formed while  $\text{Ca}^{2+}$  is available in the sarcoplasm. These effects on the SR would be difficult to observe as the effects on  $P_t$  would be masked by atrophy but are of interest on the assumption that the twitch changes are due to SR alterations. The changes in the kinetics the mechanical responses at paired

stimulation (see Fig. 2, C) might also be explained by altered development of  $\text{Ca}^{2+}$  kinetics in the muscle used in the experimental. At any given interpulse interval the relative increase in force of contraction after long-term space flight effect was significantly less compared to the pre-flight value.

### Effects of space flight on force-velocity relationship

The rate of rise of evoked contraction (the shape of the force-time curve) in response to electrical stimulation of the *n. tibialis* with a frequency of 150 impulses  $\text{s}^{-1}$  calculated according to the relative scale showed only minor changes due to microgravity, which agrees with the observations (87) of relatively constant mechanics of tetanic contraction theory of muscle contraction (74). Similar to the flight condition (a 120 days), we have previously shown that head-down tilt no significant changes in the force-velocity characteristics of human the TS muscle (44, 47) and this observation agrees with the data obtained earlier by Witzmann et al. (87), who have shown that there were no significant changes in the force-velocity characteristics of rat soleus, extensor digitorum longus or superior, and vastus lateralis muscles after 21 days of immobilization. If the shape of the force-time curve is determined by the net rate of formation and disruption of the cross-bridges (74) which are proportional to the activity of myo-ATP-ase (75), then it may be assumed that the cycling of cross-bridges and activity of myo-ATP-ase varied slightly (or not at all) during the effects of microgravity. Therefore, one can assume that inactivity of myo-ATP-ase is reason for changing the kinetics of contraction after weightlessness. This supports the hypothesis that the changes of isometric contractile properties of the microgravity skeletal muscles being in microgravity result not from a change of contractile proteins but from any other factor/s, possible, from change in the function on SR. The increase of the normalized rate of tension development ( $dP/dt$ ), that was recorded during prolonged space travel was consistent with the finding that myo-ATP-ase activity and maximal velocity of shortening have been enhanced during space flight which agrees with the observations to disuse (80). It would therefore seems reasonable to conclude that disuse, for example weightlessness or head-down tilt,

in crew prolonged space travel has little effect on either cross-bridge cycling or myosin activity (17).

In addition to, it is known, the time course of force development during electrically evoked tetani did change whereas the maximal rates tetanic force development ( $dP_{ec}/dt$ ) was increase (see Fig. 6). The cause of the space flights-induced increase in the maximal unloaded shortening velocity is unknown. However, increases in shortening velocity as a result of microgravity can also result from geometric alterations inside muscle structures, i.e., increase in filament spacing (66) or a decrease in the pennation angle of muscle fibers (24, 85).

On the other hand, the microgravity-induced increase in the maximal unloaded shortening velocity of the TS muscle could be due to at least three possible mechanisms: i) an increase in the fast type myosin heavy chains (MHC) protein isoform content; ii) the *de novo* expression of a faster MHC isoform, and/or iii) an increase in the fast myosin light chains (MLC). Previous studies at both the whole muscle (14) and single-fiber (10) level have report good correlations between the MHC isoform composition and maximal unloaded shortening velocity. Hence, the 44 % increase in the maximal rates tetanic force development ( $dP_{ec}/dt$ ) in the flight triceps surae muscles could be due to the corresponding increase in the relative fast type MHC protein isoform content. Also possible that some of the increase in maximal velocity may have been due to alterations in the essential MLC isoform composition of the flight muscles (86). Increased maximal shortening velocity might have occurred due to the selective loss of thin filaments. Such alterations have already been hypothesized by some authors. Riley et al. (72) shown that a 17 day space flight (STS-78) induced disproportionate loss of actin filaments in human soleus muscle. This structural change was responsible for post-flight increase in the maximal shortening velocity and for a reduced peak stiffness in the muscle (86). These alterations would be expected to have greater effect on shortening velocity than on force (86).

### Effects of space flight on electromechanical delay

During many everyday activities, the ability to produce high muscle force per time unit is more important than the ability to generate high force. The

rate of force development depends on many factors, in particular, on the duration of the excitation-contraction process, on the force-velocity properties of muscle fibers (even during isometric contraction due to tendon structure deformity) and SEC stiffness. Therefore, decreased MTC stiffness may be the reason for the decreased rate of development of the TS muscle contraction after unloading, since SEC stiffness is known to be an important factor determining the rate of muscle force development (9). In other words, as indicated in the Introduction, the time of SEC stretching by contractile elements determines the EMD value (38). Therefore, changes in MTC (SEC) stiffness after hyperactivity/hypoactivity mainly explain changes in EMD. In addition, all the structures of the SEC, classically composed of an active part (located in myofibrils) and a passive part (mainly aponeurosis and tendon) (88), could contribute differently to EMD. Nordez et al. (69) used the noninvasive methodology (a real-time ultrasonography) to determine the relative contribution of the passive part of the SEC ( $47.5 \pm 6.0$  % of EMD) and each of the two main structures of this component (aponeurosis and tendon, representing  $20.3 \pm 10.7$  % and  $27.6 \pm 11.4$  % of EMD, respectively).

This study demonstrated that the rate of isometric voluntary contraction development performed after the instruction to exert the fastest contraction had decreased after unloading, which confirms the theoretical relationship between the decreased muscle MTC stiffness and decreased rate of transmission of the contractile force and therefore the rate of contraction development. This data was obtained for the first time and is indicative of the increase of MTC stiffness after PT under conditions of muscular system unloading. Our results in the present study indicate that PT during space flight results in an increase in MTS (MTC), whereas a lack of PT is associated with a decrease of this parameter (53). Therefore, PT decreases the EMD under muscular system unloading conditions.

The changes in elastic properties due to PT have been well documented. Endurance training resulted in an increase in the SEC stiffness in the soleus muscle of rats, associated with an increase in type I fibres (31). Both jump and endurance training also appear to increase both collagen concentration (23, 58)

and muscle passive stiffness. The soleus rat muscles submitted to plyometric training had more fast twitch fibres and a lower SEC stiffness than controls (3, 83). Malisoux et al. (63) reported that human subjects given 8 weeks of maximal effort stretch-shortening cycle exercise training tended to have an increase in the proportion of type II fibres in their vastus lateralis muscles. Kubo et al. (60) reported that the MTS is greater in long distance runners than in untrained individuals.

The results obtained correlate well with data on the decreased EMD after isometric training under bed-rest conditions (60, 61). The EMD changes during training are mainly attributed to changes in the tendon structure, but it should be noted that tendon stiffness is always increased during any physical activity, both during endurance (12) and isometric training (60, 61). Furthermore, EMD changes correlate very closely with muscle MTC and especially with the active SEC fraction during training (22, 63).

This study demonstrated that the EMD is sensitive enough and may serve as an indirect marker for measurements of muscle MTC stiffness in order to determine the chronic adaptation of the musculo-tendinous structure of the muscle to the mechanical unloading during PT under real or simulated microgravity conditions. The data obtained demonstrates that a 180-day of actual microgravity led to decrease the TS mechanical properties and although the adverse effects were reduced thanks to PT, they were not completely prevented by the training program. This permits us to suppose that the volume of exercises and especially the intensity of exercises performed did not exceed the threshold level required for the complete prevention of changes in mechanical properties.

The mechanical muscle responses obtained and the list of physical exercises received from the study subjects, as well as from members of long-term (6-month) space missions confirm the importance of PT in preserving muscle function and the capacity to work during long-term stays under microgravity conditions. Within the framework of this study, the PT program contained mainly low intensity exercises. The inclusion of exercises with higher load and higher intensity into the training process would contribute to a more effective exercise program for the training of skeletal



muscles and it would reduce the total training time under zero gravity conditions. In general, PT under microgravity conditions allows subjects to create an increased functional reserve and reduces the effect of unloading observed under real microgravity conditions.

In conclusion, the results presented here show that mechanical properties in human the TS muscle were altered after prolonged space flight. The comparison of the mechanical alterations recorded during voluntary contractions and in contractions evoked by electrical stimulation of the motor nerve (for all seven cosmonauts studied MVC produced more decreased than  $P_0$  after the space flight), suggests that weightlessness not only modifies the peripheral processes associated with contractions, but also changes central and/or neural command of the contraction.

## VI. CONCLUSION AND RECOMMENDATIONS

The main result of our study shows the considerable reduction of contractile functions of the TS muscle, as a muscle undergoing more changes in comparison with other muscles at unloading (2). It follows that contractile characteristics of muscle depend, among others, on background of its activity. In this connection the necessity of analysis of training process arose which shown that crewmembers of space missions used cyclic type exercises as main means of training, and it appears that this was not enough for maintaining of functional characteristics of neuromuscular apparatus as executive "work" apparatus in crewmembers of prolonged space flights. In this connection it is necessary to take into account functional possibilities of the system like neuromuscular apparatus, which suffers primarily in space flight conditions, while developing the training process.

The reduction of contractile functions in space missions crewmembers supports the idea that "protection" of skeletal muscles during long-term space flight requires physical training with more effective program. The program of physical training with the use of such means of training process as treadmill and bicycle ergometer improves aerobe capacity by providing of training of cardiovascular and respiratory systems (34), but not power characteristics of muscle

apparatus. That is why the reduction of contractile functions of muscles after space flight supports the idea that "protection" of muscles during space flight requires physical training with more effective training program including in particular high-intensive and/or "explosive" exercises which increase power characteristics of muscles (73, 79), and are promising for avoiding muscles atrophy and "weakness". Besides, analysis of training process used in space flight has not revealed specific exercises aimed at the training of plantar flexors that could be additional factor in the reduction of contractile functions of muscles.

## VII. DISCLOSURES

The author has no conflict of interest in the study and has not received external financial support for the preparation of this manuscript

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