Functional Electrical Stimulation (FES) as a Countermeasure against Muscular Atrophy in Long-Term Space Flights - - First Application on Board of MIR-Station

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Abstract

Long-term flights in microgravity cause atrophy and morphological changes of skeletal muscles. Training with mechanical devices is insufficient regarding time to exercise and space for devices.

The objective of the project MYOSTIM is to develop a training method, based on FES to preserve muscle mass and fiber composition with minimal impairment to the cosmonaut.

For a pilot experiment on board of the MIR station a suitable 8-channel FES equipment was developed. It consists of electrode trousers, that carry surface electrodes and cables, two interconnected 4-channel stimulators, and a laptop-PC for stimulator programming and processing compliance data. An automatic extensive training of 4 muscle groups of the lower extremities is performed for 6 hours per day, with 1 s on / 2 s off tetanic contractions at 20 to 30% of maximum tetanic muscle force. Synchronous activation of antagonists of thigh and lower leg prevents from uncoordinated movements.

The first successful test on board of MIR was performed by 2 cosmonauts between Dec.98 and Feb.99 respectively March99 and Aug.99.

1. Introduction

Long-term flights in microgravity cause atrophy and morphological changes of skeletal muscles. Extensive daily physical training using mechanical devices raises the caloric intake, shortens the operational activities and requires extreme motivation of the crew members. The limitation for an active muscle training during a long-term space mission in terms of time and space needs the consideration of an automatic support.

Functional Electrical Stimulation (FES) is well established in terrestrial rehabilitation and sport training since years [1] [2] [3] [4]. It has a high potential to serve as an efficient counter-measure that avoids most of the cited impairments, as long as the equipment is comfortable and easy to handle under space conditions.

Fig. 1: Commander of crew 26 applying MYOSTIM on board of MIR space station

To investigate the effectiveness and practicability of FES as a countermeasure mean, a co-operation with IBPM in Moscow was established and led to the recent first two successful applications on board of MIR space station (Fig.1).

2. Material and methods

Principle of training: FES is applied to 4 musclegroups of both lower extremities. Electrodes are placed on the skin above the quadriceps femoris muscles, the hamstrings, the tibialis anterior- and peroneal muscles, and the triceps surae muscles. Synchronous stimulation of antagonistic muscle groups prevents from unwanted joint movements.

The training is performed during 6 hours per day with 1 sec “on“ and 2 sec “off“ trains at intensity levels of 20 - 30% of maximum tetanic force (MTF). Besides this extensive training mode an additional intensive training mode with a limited number of high intensity tetanic contractions is implemented.

FES is applied additionally to the Russian routine physical training program, that comprises predominantly intermittent treadmill exercises for 1-2h/day and resistance exercises with bungee-cords, organised according to a 4-day cycle (Tab. 1).

Equipment and parameters: The technical equipment consists of electrode trousers carrying EMG and stimulation electrodes for the eight channels, and two interconnected 4-channel stimulators carried on a belt. After donning the system a programming routine checks the electrode impedance and detects all threshold and saturation levels by amplitude variation of single stimulation impulses and recording of the evoked EMG reaction (M-wave). This procedure makes use of the correlation between M-wave amplitude and muscle tension and allows to determine the intensity levels for extensive (20-30 % MTF) as well as intensive training (100 % MTF) automatically for all 8 channels. After this initialization the system begins with automatic training with a default stimulation frequency of 25 Hz in extensive and 50 Hz in intensive mode. Electrode impedance and M-wave are monitored permanently to identify potential electrode problems or early signs of muscle fatigue.

Tab. 1: Russian routine countermeasure training scheme:

Day	Goal	Work load	Intensity of load	Energy expenditures
1	Maintenance of high velocity characteristics of muscle and of orthostatic tolerance	small	submaximal, maximal	380-420 kcal
2	Maintenance of muscle strenghth-velocity properties	middle	middle	450-500 kcal
3	Maintenance of endurance and of movement co-ordination	high	small	550-600 kcal
4	Active rest, physical exercices of cosmonaut´s own choice	small	ad lib.	150 kcal

Evaluation: Evaluation is done in accordance with the standard protocol of the Moscow IBMP, which is routinely used to investigate the effectiveness of various countermeasure means. The protocol contains physiological as well as morphological preflight and postflight examinations, and ergometric tests during flight. In addition the stimulation device records and stores stimulation intensity, M-wave and impedance data.

3. Results

The work of the Vienna research team was focused on technical and technological research and development. A practical solution was found for the electrode trousers (Fig. 2). Placement of the electrodes to the skin is simplified by a patented construction of two flexible flaps, carrying the electrodes and corresponding protection foils, that are alternatively exposed to the skin.

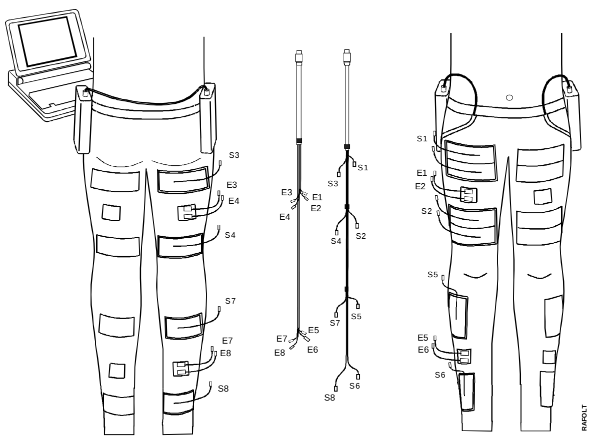

Fig. 2: Electrode configuration and principle of equipment design, cables and electrodes integrated in electrode trousers.

The developed stimulation equipment consists of the circuitry for M-wave and impedance-recording, the stimulation output stage, micro-controllers for impulse generation and measurement purposes (one for each channel), a co-ordinating micro-controller, the power supply, the graphical display, control elements and a bus-interface. The 8-channel stimulator is divided into two 4-channel modules interconnected by an I2C-bus (Fig. 3). The circuitry is miniaturised in SMD (surface mounted device) technology and integrated in a robust metal case. All stimulation and training parameters can be set by a personal computer (PC) via an RS232 link. The training protocol is transferred weekly to the PC via the RS232 link and stored in a database.

All technical solutions were tested in-vivo and underwent the standardized Russian qualification and certification test procedures.

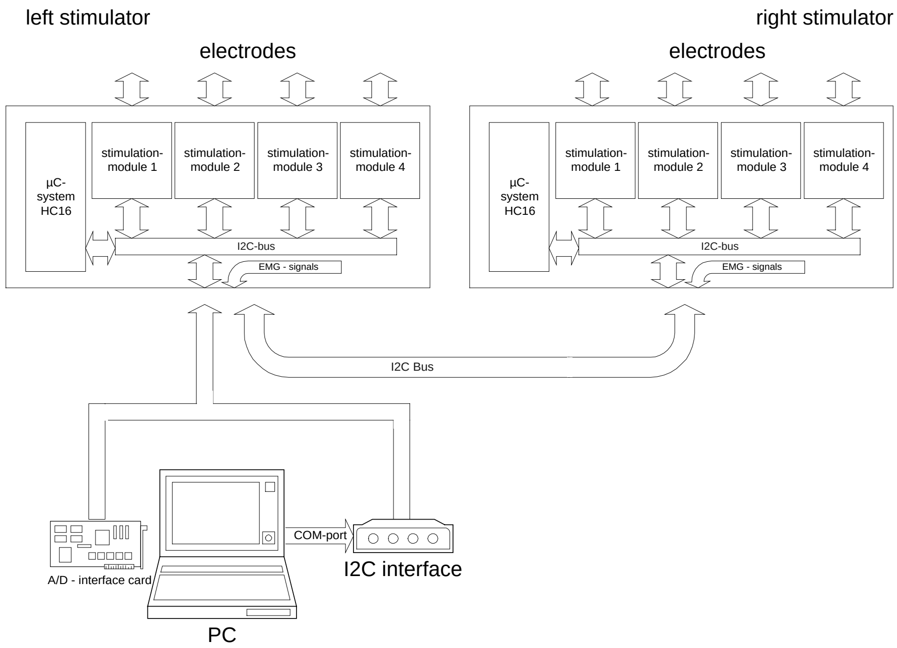

Fig. 3: System configuration with two 4-channel stimulation modules and the Laptop-PC for programming parameters, storing the compliance protocol and controlling measurement procedures.

The equipment was transported to the MIR space station for the first applications on October 27, 1998. It was successfully applied by one cosmonaut between December 98 and February 99 (Fig. 1) and by a second cosmonaut between March 99 and August 99. Both cosmonauts went to MIR station in August 98 and used the equipment in a later phase of their flight and then continuously till their landing. Up to now only data of the first of the two applications are available.

During this first pilot application MYOSTIM was used for 3 hours per day at intensity levels of 20-30 % MTF additionally to the routine physical training program. 4 control cosmonauts from different missions with similar flight duration performed only the routine on-board countermeasure training and no FES (Tab. 1). The compliance of training in volume and intensity was between 80 and 100 %.

The Russian documentation, which was sent to us recently, showed promising results of the first MYOSTIM application during a long-term space flight. It has provided us with data of both handling of the equipment in microgravity and effectiveness of FES muscle training in space. However, we have only pilot results and further systematic investigations are absolutely required.

In comparison to the control cosmonauts of crew 26 and crew 27, who used only the routine countermeasure physical exercise program, the commander of crew 26, who used in addition MYOSTIM, was in much better condition during flight and after landing. This was the significant outcome of the *ergometric locomotion tests* performed pre- and post-flight and during flight, where he showed, in comparison to his colleagues, much lower heart rate and lactate levels in all phases.

Muscle contraction dynamics, investigated with tendometry (Tab. 2) and dynamometry, showed clearly better values in post-flight investigations, again in comparison to cosmonauts who did not use MYOSTIM.

Tab. 2: Tendometry, triceps sure, changes in relation to pre-flight values:

		Cosmonaut with routine physical training + FES	4 cosmonauts, similar training except FES
Single twitch	Peak amplitude	+134,5 %	-8,3 %
	Time to peak	+12,4 %	+4,0 %
	Half relaxation time	-2,4 %	-23,4 %
Maximum voluntary contraction	Peak amplitude	-27,1 %	-43,5 %
Maximum stimulated contraction	Peak amplitude	-12,9 %	-27,1 %

The *histo-morphological investigations* did show a similar reduction of fiber cross sectional area (CSA), when compared with the control results, but the typical atrophy-related increase of interfascicular connective tissue did not appear in the FES trained muscle. In contrary a decrease from 11% to 6% was observed. Cytochrome-C-oxidase indicated a substantial increase of aerobic metabolism of both type 1 (+152%) and type 2 fibers (+131%), an effect that was emphasized by an increase of capillary density by +174,5 %.

The positive influence of additional FES training was further confirmed in the *posture stability tests* and in *reflex tests*, that showed significantly better results and a much earlier recovery.

The *subjective judgement* of both cosmonauts was extremely positive: There were no complains concerning daily handling of the equipment over month and practicability of the training during work, except seldom extremely fine-motorial tasks, when they had to switch of the stimulation temporarily. The reported improved fitness and wellbeing, the feeling of "complete muscle integrity" and the lack of previously experienced muscle pain.

4. Discussion

To substitute the terrestrial muscular load during long term space flights exercise and training programs are required. The training and the devices consume extensively time and space, an alternative would be helpful. The objective of our project was to provide an alternative method for avoiding or at least reducing the changes in the skeleto-muscular system with minimal impairment to the cosmonaut.

Morphologically microgravity causes a loss of muscle mass and a reduction of type I muscle fibers, which are responsible for muscle tone and posture above all. It is common knowledge that extensive FES training tends to transform type II to type I fibers, an effect that seams to be useful to compensate the type I fiber loss in microgravity [5] [6].

The level of 20 to 30% of MTF was chosen to achieve substantial training at minimal sensible inconvenience. Simultaneous activation of antagonistic muscle groups prevents from unpleasant movements. The first test under space conditions showed, that this isometric low level training is comfortable and does not interfere with daily operational activities.

An exact simulation of terrestrial muscular activity cannot be expected from stimulation via surface electrodes. Distribution of fiber types in an FES trained muscle will always differ from a normal muscle. This effect is known to be totally reversible within several weeks after end of stimulation training under normal muscular activity, i.e. under terrestrial conditions [7] [8].

The results of the functional tests, the faster functional recovery and the subjective judgement of the cosmonaut, who had already experienced a long-term flight without FES training previously, lead to the assumption, that - besides pure muscle preservation - a major benefit of daily extensive low level FES training lies in the stimulation of the proprioceptive system and induction of afferent activity.

The first applications in space have provided us with data of both handling of the equipment in microgravity and effectiveness of FES muscle training in space. However, we have only pilot results, that call for further systematic investigations. Provided that the technique further proves to be effective, the application should be extended to the trunk and neck muscles to preserve posture of the cosmonauts.

Profit for terrestrial applications in medicine can be expected, as long-term immobilization causes morphological changes in skeletal muscles, similar to those in microgravity. A clinical study including 42 patients, suffering from severe chronic heart insufficiency, where MYOSTIM was applied for muscle training, resulted in a significant improvement in the patients´ mobility and in a transfer of the method to clinical routine application [9].

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