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Eye, Head and Arm Coordination and Spinal Reflexes in Weightlessness – MONIMIR Experiment*

1. Introduction

One of the most important fields of research being conducted in space medicine concerns the effect of weightlessness on the human locomotor system and its control systems in the central nervous system. Under terrestrial conditions, the earth's gravitational field constantly influences all sensory motor functions. Only by adapting to gravity is it possible for man to assume an erect posture. Studies of human motor functions under microgravity offer new possibilities for analyzing the sensory motor systems and their influence on posture and motion.

Studies of movement conducted in simulated weightlessness using hypokinesia and immersion models have revealed that in weightlessness motor disturbances are characterized by changes in all aspects of motor function. Motor disturbances in microgravity are manifested in reduced accuracy of movement, of target finding and in an increase in motor reaction time. Complex motor disturbances in real and simulated weightlessness are known under the name hypogravitational ataxia syndrome. The characteristics of this symptom complex, also known as the space adaptation syndrome, are primarily motor disturbances in the form of reduced muscle tone with simultaneous hyperreflexia, reduced strength of muscle contraction, reduced motor accuracy and disturbed motor coordination. Also observed are disturbances in the control of posture and sensation of motion and of body scheme, but also distur-

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bances of the dissociated sensibility qualities. Alertness (vigilance) is decreased and the psychomotor functions diminished. In real weightlessness, some of these deficiencies can be minimized or even prevented by intensive exercise.

Project Monimir was set up to study the disturbance in movement coordination occurring in healthy persons under weightlessness. Newly developed devices permit us to record and quantitatively analyze different movement of the eyes, head and arm following stimulation with visual, acoustic or proprioceptive stimuli.

In real, nonsimulated weightlessness, a functional deafferentation of gravitational receptors permits us to assume a disturbance in the biomechanical function of the spine, particularly in the cervical spine, with possible disturbances in body scheme and position.

Functional deafferentation of the gravitational receptors, particularly of the receptors of the neck muscles, as well as of the vestibular apparatus lead us to expect disturbances in voluntary and extrapyramidal motor function in real and simulated weightlessness. Conclusions on spinal reflex mechanisms can be drawn from a study of the T reflex.

2. Test Program

In order to study the influence of weightlessness on coordinated and aiming movements, a number of individual tests were conducted in the framework of Project Monimir. The test program also included two projects concerned with the biomechanics of the cervical spine and with spinal reflexes.

2.1. Study of State of Motor Control Systems in Real Microgravity

2.1.1. Study of time and kinematic performance of preprogrammed and feedback-controlled movements of the eyes, head an arm, stimulated by acoustic, visual and proprioceptive stimuli

2.1.2. Study of the influence of visual control on the accuracy of various aiming movements

2.1.3. Study of the influence of weightlessness on motor short-term memory of head and arm movements trained by proprioceptive and visual feedback

2.1.4. Study of the influence of neck proprioceptors on the accuracy of arm movements

2.2. Study of the Biomechanics of the Cervical Spine Under Weightlessness

2.3. Study of Spinal Reflexes

Study of the influence of weightlessness on the state of spinal motor centers by examining the T reflex with the aid of a patellar tendon reflex under standardized triggering using the Innsbruck automated reflex hammer (Fig. 1).

Fig. 1. Patellar tendon reflex elicited by reflex stimulator in the MIR simulator

3. Technical Description

The Monimir apparatus consisted of an optoelectronic system for recording movement, an LED (light emitting diode) matrix, biosignal amplifiers and a system for eliciting tendon reflexes.

The PC interfaces were an ADC (analogous digital converter) card for analogue data and a digital input-output (DIO) interface for digital data (Fig. 2). Visual signals for standardized eye and head movements

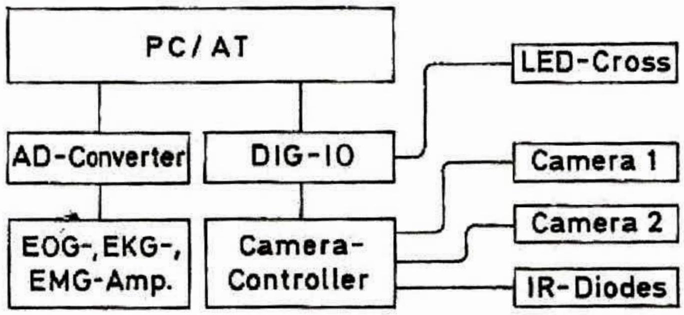

Fig. 2. Schematic Diagram of the MONIMIR Equipment

were given by an LED matrix with PC-controlled, x-shaped LED (light-emitting diodes). The optoelectronic system for recording movement consisted of two cameras, eight infrared diodes for signals and a system unit. In order to record head movement, the test person wore a helmet with five pairs of infrared diodes as markers (Fig. 3). Arm movements were recorded with an arm lamp fixed to the test person's lower arm. The arm lamp was equipped with two pairs of diodes. The paired arrangement of infrared diodes enhanced their visibility for the cameras. The diodes in each pair were arranged at right angle to each other and flashed simultaneously, so that each camera captured one diode of each pair. These infrared diodes were activated in a preset sequence in time multiplex synchronous to the camera's exposure clock. With the aid of newly developed cameras (two CCD linear image arrays per coordinate), the signals of the infrared diodes were recorded and digitized, so that for each infrared diode each camera sends only one set of x and y pixels to the computer. The use of two cameras made three-dimensional position coordination of the infrared diodes possible.

Fig. 3. Test person during test with helmet, acoustic system and operator box. For registration of head movements, infrared diodes fixed to helmet, picked up by 2 x 2 infrared scanner cameras. For control of aiming accuracy of head movements and subsequent correction of head positions, a focused light beam (helmlamp) switched on with the gun's trigger. EOG, EMG and EKG amplifiers built into the operator box

Each camera contained two CCD sensors (charge-coupled devices) arranged at right angle to each other. Each CCD line had a resolution of 1728 pixels. Rigidly fixed to it was the visual system consisting of a cylindrical lens and a visual low-pass filter, which together with the wave length-dependent sensitivity of the CCD sensor gave a visual band filter of 830 - 940 nm. Since the device was not designed for experiments in direct sunlight, this filter only had to eliminate the influence of artificial illumination (neon lamps). The analogue video signal was already analyzed and digitized in the camera. For this purpose, a trigger level was determined for the analogue video signal by means of a comparator. The CCD sensor was read by the data clock. The number of pixels was counted synchronously by the data clock. When the comparator's trigger level was exceeded by the video signal amplitude, the number of pixels was stored. When the video signal dropped below this value, the number of pixels was added to the preceding value and stored in the PC. This simple form of analysis was possible because the analogue video signal given off by the infrared diode was symmetric in time in the vicinity of its peak.

The test is schematically illustrated in Fig. 4. The system's technical data are given in Table 1.

Table 1. Summary of System's Technical Data

ADC:	
Channels	16
Sampling frequency	200/Hz/channel
Video System:	
Markers up to 8 IR diodes	
Cameras two with 2 CCD linear image arrays each	
Accuracy + 0.5 mm in x, y and z direction at a camera distance of 7 m	
Field of view 36° (x and y direction)	
Framing rate 25 frames/s	

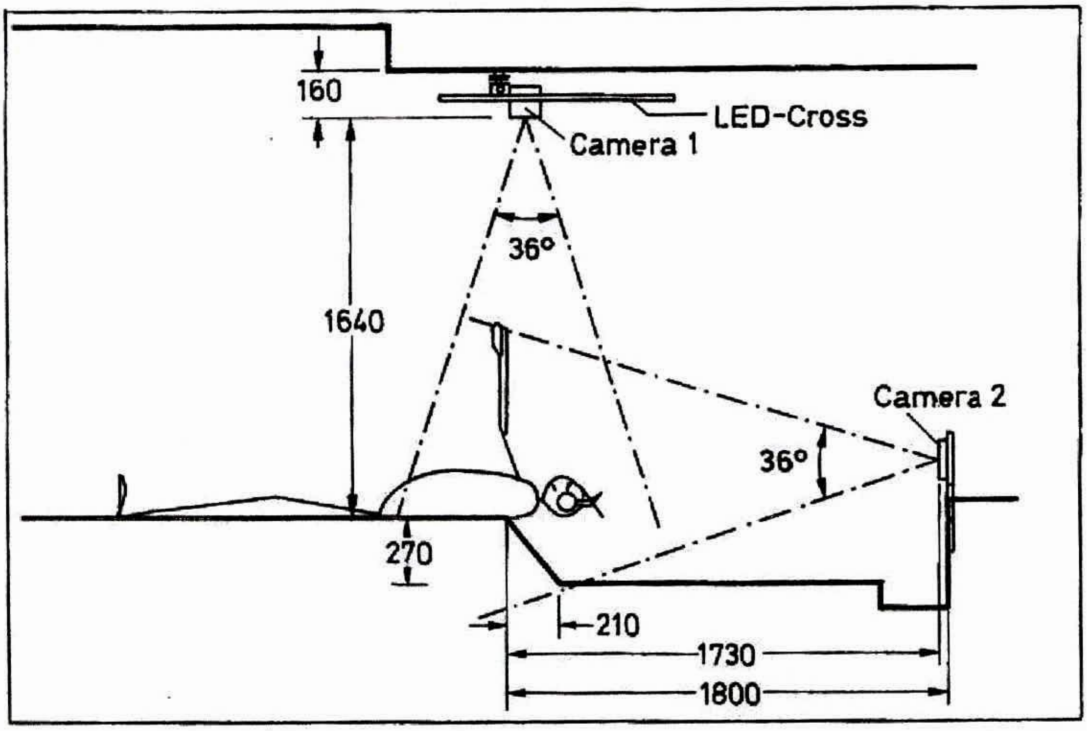

Fig. 4. Schematic drawing of test situation in the MIR Space Station.
Test person lies on the "floor" of the space station with trunk fixed; head freely moveable above a depression; head (helmet with lamp) and arm movement (arm lamp) registered by 2 x 2 infrared 1D CCD image sensors; cameras mounted in front of face (camera 1) and in body's longitudinal axis (camera 2); visual targets presented on LED matrix mounted with camera system 1

4. Execution of Project Monimir

The Monimir experiment was conducted thirty-six days before flight, on flight days 2 and 5 as well as 24 hours after landing. Figure 5 shows the cosmonauts during a training session in the simulation model of the MIR Space Station. The following will report on the separate test programs conducted and explain the neurophysiological basis.

4.1. Study of State of Motor Control Systems in Real Microgravity

4.1.1. Preprogrammed, rapid aiming movement:
Rapid aiming movements without direct feedback were executed and integrated in the central nervous system as final motor patterns. The execution of each voluntary motor pattern was controlled by an efference copy and the motor results continually optimized.

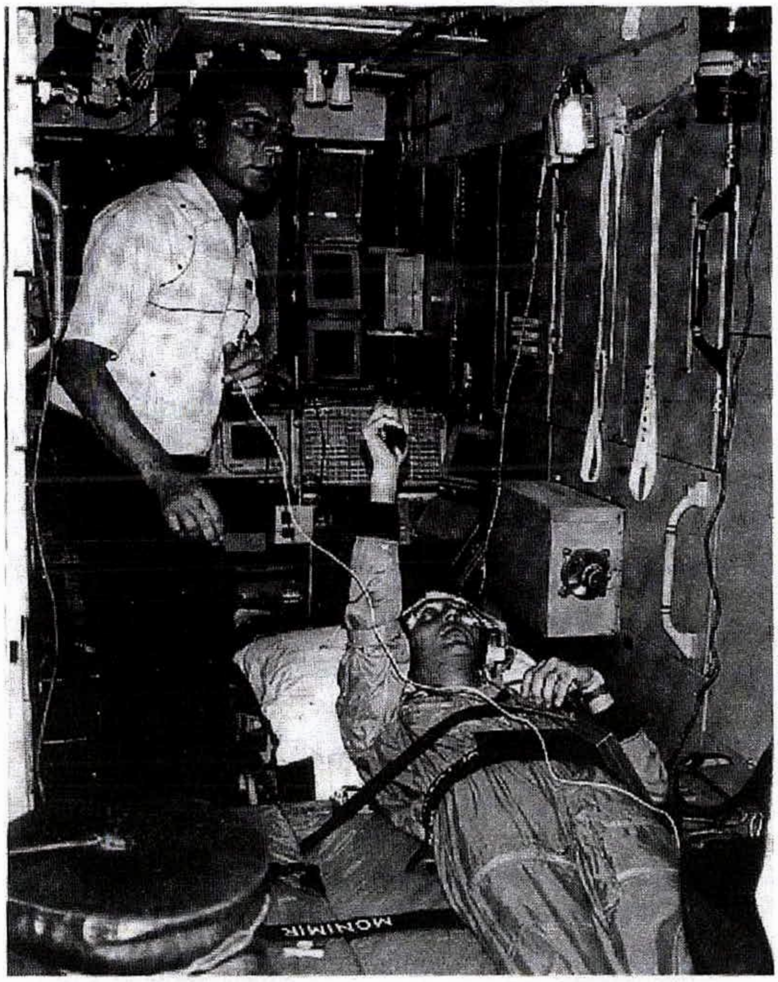

Fig. 5. Monimir ground experiment in the MIR simulator:
LED matrix with camera system 1 fixed to ceiling cosmonaut fixed to floor while executing aiming movements

Tests were conducted with visual and acoustic signals:

4.1.1.1. Aiming movements on visual signals:

Aiming movements of eyes, head and the arm on points of light briefly presented on the LED matrix in horizontal and vertical directions. Each time the target was hit, the head or arm lamp lit up. In this way, a miss was apparent and correction possible.

4.1.1.2. Aiming movements on acoustic signals:

Acoustic signals were given at a certain angle on a horizontal level through headphones. The signals were answered with aiming movements toward the signal and execution was recorded. Hits were signaled by the head or arm lamp. This test was conducted with the test person's eyes closed and open.

4.1.2. Tracking movements on a stimulus:
Slow tracking movements were made by feedback under constant control of motor performance. Visual control and proprioceptive input of the movement permitted running adaptation of motor activity to the particular demands. The test consisted of movements following visual stimuli. A steady tracking movement made with the eyes, head or arm was given in response to rapid visual signals (serially flashing markers) to the LED matrix in horizontal and vertical direction.

4.1.3. "Motor memory" of learned aiming movements:
This test examined the reproducibility of motor patterns and consisted of two parts.

4.1.3.1. Passive arm movement:
A figure was shown on the LED matrix. A second cosmonaut traced the outstretched test person's arm along its outline with the test person's eyes closed. Afterwards these passively performed movements were actively repeated from memory.

4.1.3.2. Active arm movement:
The test person actively traced the visually given pattern with his arm and then repeated this movement without visual control.

4.1.4. Postural and labyrinthian reflexes:
Postural and labyrinthian reflexes are essential components of the human motor functions responsible for posture and motion. The head movements necessary for postural and labyrinthian reflexes are influenced by receptors in the upper cervical spine. Changes in the flow of information from these receptors, that are caused by reduced muscle tension under weightlessness, could cause changes in the motor functions involved in postural and labyrinthian reflexes. For this test, arm movements were executed with the head in various positions.

4.2. Biomechanics of the Cervical Spine

The cervical spine moves the head in six dimensions, namely in three axial rotational axes and three translation coordinates. For this test, the head was rotated to the left and right, nodded forward and back, and bent to both sides. Analysis of the six-dimensional motor patterns is expected to provide information on changed motor functions in the individual cervical vertebrae.

4.3. Spinal Reflexes

In order to study the excitability on spinal level the patellar tendon reflex was used. A standardized mechanical stimulus applied to the knee tendon with a hammer permitted us to measure a reflectory extension of the knee joint. The activity of the musculus quadriceps femoris was determined by electromyography. The automated performance of the reflex hammer and the ensuing extension of the knee joint were registered.

5. Preliminary Study Results

Analysis of the data of eleven complete Monimir test programs provided the following preliminary results. The results of the individual experiments are summarized and given in block form.

5.1. State of Motor Control Systems in Real Microgravity

Before flight, all preprogrammed head movements to visual targets were executed with standardized, regular parameters (Exp. 4.1.1.1). In real weightlessness, the variance of time and amplitude increased. In determining the final target, a considerable error was observed in moving the head toward the given target and back to its starting position. The mean value of error for head movement increased slightly during flight (Fig. 6). The number of correct hits without correcting movement (Exp. 4.1.1.1) decreased to one on flight day 2 and to three on flight day 5 out of a total of 22 movements executed. The number of correcting movements under visual control markedly increased during flight (from 65% before takeoff to 85% during flight, n=22), whereby a large number of these corrections were clearly less successful (60% failed corrections on flight day 2, 80% on flight day 5, n=22), thereby reducing the number of precise movements. Motor reaction time for the movements was also different (Exp. 4.1.1.1, 4.1.1.2). Both a moderate decrease in mean and maximum velocity of head movement was observed as well

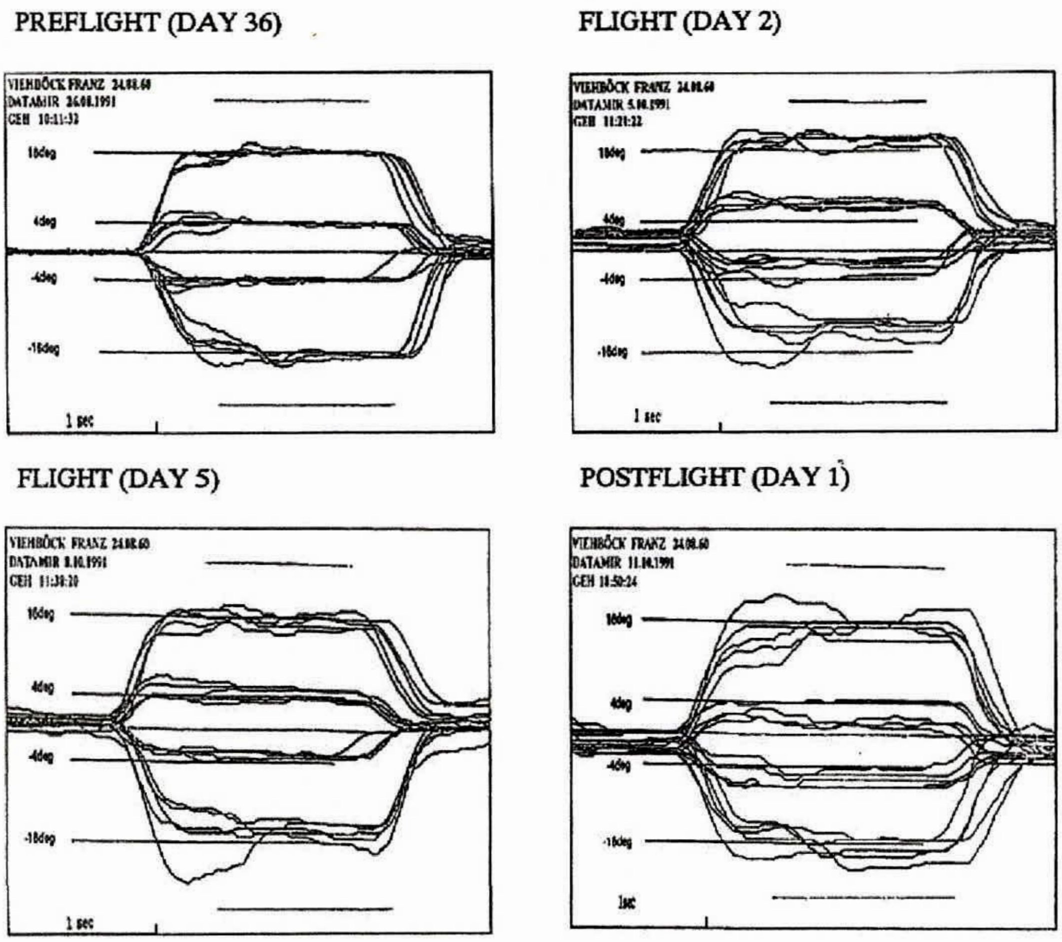

Fig. 6. Rapid, preprogrammed head movements under visual control on LED signals before flight (day 36), on flight days 2 and 5 and postflight (first day) (supraposition of 22 horizontal head movements)

Legend:
Horizontal head movement (n=22) on visual signal (4° or 16° right and left). Preflight test: standardized execution of movements with accurate, reliable, preprogrammed head movement (training goal reached)
In-flight tests:
Flight day 2: Decrease in velocity and accuracy of movement with hypermetria and oscillation after hitting target
Flight day 5: Signs of adaptation with continued reduction in velocity of movement
Postflight test:
New markedly disturbed motor pattern with considerable variance (hyper/hypometria)

as an increase in duration of head movement to acoustic and visual signals.

When moving the head toward a target at a small angle (4 degrees), the time needed to find the target markedly increased (from approx.

600 ms to approx. 1000 ms) (Exp. 4.1.1.1). When testing head movement to visual signals in weightlessness, a decrease in mean head velocity was observed while maintaining the same velocity of opposite eye movement.

A new program for eye-head coordination trained shortly before flight for head movement to acoustic signals (Exp. 4.1.1.2) and simultaneous gaze fixation of the closed eyes on an imaginary midpoint (converse eye-head movement) was abandoned on flight day 2 in favor of the former coordination pattern (head movement to target with spontaneous synkinesis of the eyes). Only on flight day 5 were the original parameters regained (Fig. 7).

In the case of slow tracking movements of the head and arm on a moving light signal (Exp. 4.1.2), no noteworthy in-flight deviation occurred under visual control. This shows the importance of visual feedback for slow tracking movements in weightlessness.

When testing short-term motor memory, arm and head movements (task = triangle) are learned under visual control or by passive movement of the arm by another person without visual control and then repeated several times with closed eyes (Exp. 4.1.3.1). Before flight, the movements were largely identical. Inflight, the motor patterns changed, in that the size of the triangle was enlarged at each repetition and the center of mass moved downward. These changes were more pronounced on flight day 5 than on flight day 2; no adaptation occurred. Particularly pronounced disturbances were also seen for passively learned movements (Exp. 4.1.3.1).

The "neck reflex" experiment studied the influence of the neck receptors on horizontal arm movement (Exp. 4.1.4). Stimulation of the neck receptors by assuming various head positions (rotation, sidebending) normally caused a slight change in horizontal arm movement. In flight, sidebending the head to the right caused the arm's horizontal movement pattern to turn counterclockwise in a frontal plane. This phenomenon increased on flight day 5 and returned to normal after landing. This might be interpreted as an expression of a body scheme disturbance.

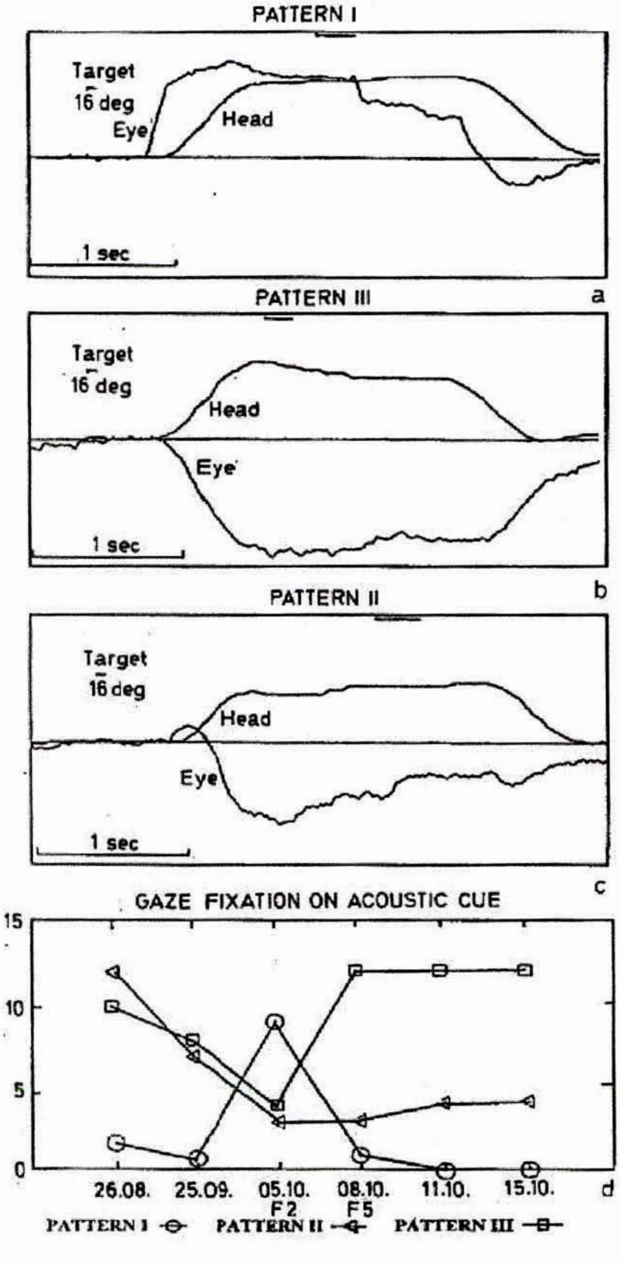

Fig. 7. Rapid, preprogrammed head movement on acoustic signal in space with eyes closed

Legend:
Motor Pattern 1 (a): movement of head and eyes in direction of acoustic target (physiologic pattern)
Motor pattern 2 (c): phase of learning counterrotation of eye and head movements
Motor pattern 3 (b): counterrotation of eye and head movement
Distribution of movement patterns (d): marked decrease in motor pattern 3 on flight day 2 and concentrated use of physiologic motor coordination, adaptation on flight day 5

5.2. Biomechanics

In order to study the biomechanics of the cervical spine, the head was moved slowly (rotated, flexed/extended and bent to the side).

When analyzing three-dimensional head movements, an asymmetric flexion-synkinesis was observed during rotation, that started at 10° when returning from a right rotation. This synkinesis decreased in the first in-flight test and was only minimally demonstrable. In the second in-flight test, the flexion occurred again in a left rotation and increased in post-flight testing.

Before flight, the rotation/lateroflexion synkinesis was asymmetric in the sense of an increased lateroflexion in left rotation. In the first and second in-flight tests, a symmetric motor pattern and a smoothing of the originally somewhat stepped motor pattern was observed, while post-flight movement again approached the pre-flight pattern.

These phenomena are considered symptoms of an adapted motor function of the cervical spine during the first days in weightlessness, since the motor patterns in the second in-flight test already approximated terrestrial patterns.

It is assumed that the change in the head's motor function also causes a change in the proprioceptive afference pattern from the upper cervical spine.

5.3. Spinal Reflexes

Quantitative analysis of spinal reflex mechanisms by means of the patellar tendon reflex showed a marked hyperexcitability at the spinal level in weightlessness. This was expressed in the increase in and changing pattern of EMG response as well as in the occurrence of a clonus in response to standardized reflex stimulation (Fig. 8).

6. Discussion

The adaptation to extreme conditions of weightlessness that is needed in spaceflight represents an ideal model for examining sensory motor adaptive processes. The test methods developed, the design of

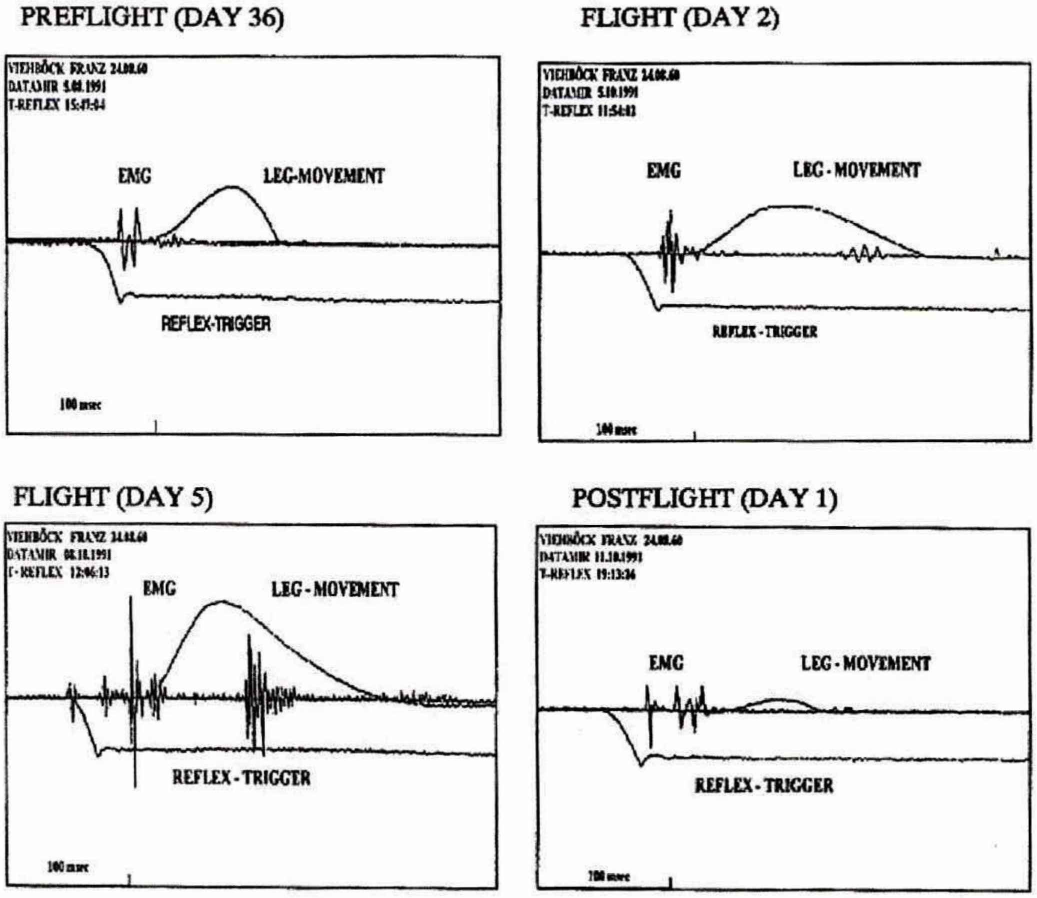

Fig. 8. Test of patellar tendon reflex by means of reflex stimulator pre-, in-, and postflight

Legend:
EMG signal of the m. quadriceps femoris, of leg movement (knee extension) and movement of reflex hammer.
Preflight: physiological patellar tendon reflex
Flight day 2: hyperreflexia with increase in EMG amplitude, duration of leg movement and occurrence of a clonus
Flight day 5: marked increase in reflex activity (amplitude, clonus)
Postflight: return of physiologic patellar tendon reflex or hyporeflexia

entirely new devices and the relevant operating and analysis software open a new approach to researching human motor systems. The new findings are expected to contribute to our knowledge of sensory motor physiology. The findings made to date show that because of the functional deafferentation occurring in weightlessness the portion of changed proprioceptive information could be a contributing factor in disturbing motor coordination.

Analysis of the data before, during and after the flight showed marked changes in motor programming. This was evidenced in disturbances in motor patterns as well as in time and amplitude characteristics.

The bedrest syndrome resulting from physical inactivity causes motor disorders through the partial deafferentation occurring in the partial weightlessness of a horizontal position. This bedrest syndrome corresponds to the space adaptation syndrome. A bedrest syndrome is observed in heart attack patients, in the long-term coma (apallic syndrome), spinal, pelvic and leg injuries as well as in bedridden elderly patients. It is seen to be largely identical to the space adaptation syndrome in terms of muscular atrophy, motor disturbances, disturbances of sense of posture and other sensory disorders as well as alertness disturbances. The consequences are a diminished resistance and, in the elderly, confusion.

The newly designed devices can be used to control the course of a neurologic disorder such as strokes, cerebral tumors, cerebral hemorrhage, coma etc., as well as for conditions following physical inactivity and provide information on the type and extent of the disorder.

Disturbed eye, head and arm coordination is observed in neurological disorders, particularly the long-term coma state, as well as in Parkinson's disease, multiple sclerosis, etc. and in conditions following whiplash.

A further result of research in space medicine is the development of modern devices to help stimulate the receptors for posture control. These devices can be used for bedridden patients, particularly the elderly, but also for patients in long-term comas. Today already, findings made in space medical research are being applied to neurorehabilitation in certain physiotherapeutic methods. The dry water immersion model can be used for the early diagnosis of neurological disorders such as the Parkinson syndrome, cerebellar disorders, spastic paralysis etc., but also to control medication regimens.

The automatic reflex hammer can be applied for the diagnosis of peripheral and central motor disturbances as well as to monitor the efficiency of antispastic drugs.

The knowhow acquired in the development of medical methods, in the development and construction of flight hardware as well as in the practical execution of space medical experiments form the basis for additional activities in space medicine.

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