SENSORIMOTOR AND PERCEPTUAL FUNCTION OF MUSCLE PROPRIOCEPTION IN MICROGRAVITY

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Abstract — Adaptive properties of the human proprioceptive systems were studied during the French-Soviet orbital flight (Aragatz mission, December 1988). The present space experiment investigated the hypothesis that the modifications of both biomechanical and physiological conditions occurring under microgravity involve considerable reorganization of body perception and postural control. The proprioceptive information originating in muscles is known to contribute, together with visual, vestibular, and sole cutaneous information to postural regulation. Moreover, by specifically activating the proprioceptive channel, muscle vibration is able to elicit both illusory movement sensations and postural responses. This experimental tool was used in microgravity in order to test various aspects of muscle sensory function. Ankle flexor and extensor vibration was applied under different experimental conditions. Quantitative analysis of motor responses was carried out on leg muscle EMG, goniometric, and kinesigraphic recordings. Joystick recordings and astronauts’ comments were used to describe the kinaesthetic sensations. The main results were as follows: 1) Under microgravity, the sensitivity of muscle receptors remains unchanged. 2) During the flight, the tonic vibration reflexes (TVR) increased significantly in flexor muscles, which exhibited a sustained tonic activity. 3) The whole-body postural responses normally induced by ankle flexor muscle vibration were suppressed, whereas they remained unchanged or were only reduced when vibrations were applied to the ankle extensor muscles. In all cases, the postural response velocity decreased. 4) A disfacilitation of the vibration-induced postural illusions was observed to occur during long-term exposure to microgravity. These illusions became atypical however. For example: body lift illusion could be induced by tibialis anterior muscle vibration, whereas it was never induced in the controls. The characteristics of the illusory body movements described under normal gravity can be restored by artificially increasing the axial foot support forces during the flight. In conclusion, these data suggest that a functional reorganization of the proprioceptive information processing occurs in microgravity, affecting both perceptual and motor aspects of behavior. It is possible that these proprioceptive adaptations may be partly attributable to the new whole-body propulsive foot functions imposed by exposure to weightlessness and to the adaptation of motor behavior to the third dimension of space.

Keywords — proprioception; posture; kinaesthesia; vibration; microgravity; Man; adaptation; weightlessness.

Introduction

Under weightless conditions, the sensorimotor mechanisms involved in the postural orientation of the body undergo considerable changes (1), moreover a redistribution of the flexor and extensor muscle activity occurs (2). During parabolic flight, subjects have, furthermore, reported the illusory feeling that either the vehicle walls or floor or their own body parts were moving (3,4). Changes in limb position sense have also been found to occur in weightlessness in the absence of visual control (5,6). A greatly impaired ability to assess
the mass of the subject’s own body or one of its parts and that of external objects (7) has also been observed in subjects under microgravity. Crewmembers’ perceptions of their bodies and their relationship with the action field, and the associated motor activities, gradually undergo adaptive changes during long space flight, but normal perception is generally recovered within a few days when they return to a normal gravity environment (5,8,9).

Awareness of the body, its postural configuration, its movements, and its orientation in the surrounding environment is built up on the basis of sensory information of various kinds arising both from the body itself and from the environment. Although vision plays a leading role in man, it is accompanied by a whole set of other information of vestibular, muscle proprioceptive, and cutaneous origin. The combined processing of all this information by the CNS results in the setting up of a postural frame of reference (the so-called body scheme), which is oriented in relation to gravity (10-15). All spatially oriented behaviour is organized within this basic framework. During the last 20 years or so, numerous experimental studies have shown that sensory information of muscle proprioceptive origin makes a decisive contribution to setting up a sense of movement and awareness of the position of the body and its segments (16,17) by showing in particular that activating this sensory pathway by tendon vibration elicits kinaesthetic sensations and alters the subject’s perception of his whole body or limb position.

Because of the biomechanical constraints involved, particularly the weightlessness of the body and its segments, microgravity is thought to induce a change in the level at which the muscle mechanoreceptors are acting. There are two possible reasons for this change: the first has to do with the modifications of the muscle activity required to maintain posture and to perform movements; the second is that the excitatory influences exerted by the vestibular system on muscle receptors, via the gamma fusimotor system, may also be altered. This would mean that the changes in muscle receptor activity induced by microgravity might affect not only the working of the postural and segmental reflex control loops that receive these signals, but also the basic processes subserving the perception and the spatial orientation of the body. These changes might furthermore be one of the causes of space motion-sickness, since they lead to the activity of the various sensory channels being decorrelated.

Among the sensory channels in question, the proprioceptive one can be experimentally activated by means of tendon vibration. Mechanical vibration applied to the muscle tendons is known to selectively activate muscle receptors (especially muscle spindles) in human subjects (18-21).

It is therefore possible to specifically activate muscle proprioceptors in order to test in weightlessness various aspects of muscle sensory function, such as

- the sensitivity of the muscle receptors,
- the excitability of the automatic posture-assisting reflex loops (22,23),
- the central nervous mechanisms responsible for postural programming and control (24, 15);
- the neural processes involved in the movement perception and the spatial orientation of the body (16,26).

Motor and perceptual effects of this kind depend, in addition, on the postural, sensory, and environmental context in which the vibration is applied (23,27). They are particularly sensitive to the presence of other sensory inputs, such as those of vestibular, visual, or tactile origin. Our knowledge of the effects listed above makes it possible to investigate how muscle proprioceptive function adapts to long periods of exposure to microgravity at both low (receptors, reflexes) and higher levels of integration (perceptual processes).

Muscle proprioceptive function was explored using tendon vibration during this spaceflight, and the various types of motor and kinaesthetic responses induced were compared with those recorded with the same type of stimulation prior to the flight. The main
results we obtained indicate that the muscle sensory receptors were still functional in weightlessness, but that the motor and perceptual responses of proprioceptive origin underwent a considerable amount of reorganization. The changes in muscle proprioceptive function observed in weightlessness seem to be attributable in general to the need to adapt the central mechanisms' integrating muscle proprioceptive data to the new behavioural possibilities associated with microgravity.

**Material and Methods**

In the present study, we investigated the postural motor effects and the kinaesthetic effects induced by applying mechanical vibration to the ankle muscle tendons before, during and after a 25-day spaceflight.

Inertial vibrators were applied to the distal tendons of the tibialis anterior and soleus muscles of both legs and held in place with elastic bands. The vibration frequency was 70 ± 5 Hz and the duration was either 5 or 10 seconds, depending on the experimental situation.

The following parameters were recorded and analysed:

- the electromyographic (EMG) activity of the tibialis anterior, the soleus, the quadriceps femoris, and the biceps femoris muscles was recorded on the right leg by means of surface electrodes;
- ankle angles were measured using an electronic goniometer;
- whole-body movements were measured using a kinetograph (VICON) which computed the trajectories of 8 retroreflective markers placed on one side of the subject. Two markers were on the head, one on the shoulder, two on the hip, one on the knee rotation point, one on the ankle, and one on the foot.
- sensations of body movement were reported verbally by the subjects and recorded on tape, as well as being quantified during the experiments by means of a joystick (Superpocket) held in the subject's right hand.

**Subjects and Test Schedule**

The study was carried out on two astronauts, subject A (SA) and subject B (SB) before, during, and after the 25-day French-Soviet spaceflight (Mission: Aragatz; Experiment: Physalie 056 in December 1988).

Each subject was tested three times prior to the flight: SA 60 days (F-60), 35 days (F-35), and 6 days (F-6) before the flight, and SB 67 days (F-67), 36 days (F-36), and 6 days (F-6) before the flight. The in-flight tests were carried out on the 8th day (FD 8) and 21st day (FD 21) in the case of SA, and on the 20th day (FD 20) in that of SB. The postflight tests took place 2 (R+2) and 6 (R+6) days after return with SA and 11 (R+11) days after return with SB (the latter subject spent a further period of 4 months and 21 days on the MIR orbital station after SA had landed).

**Procedure**

In all the tests, the subjects kept their eyes closed and tendon vibration was applied separately to each pair of muscles (tibialis anterior or soleus). The stimulus duration was of 10 seconds to test the kinaesthetic responses and 5 seconds in the study of motor responses.

The tests were run under four different experimental conditions:

1-Erect or flexed posture. In the erect position, the standing subjects had their feet attached to a platform. The subjects were also tested in the flexed position (in which the ankle, knee, and hip joints were all actively maintained at approximately 90°) in flight only. In both cases, the direction of the vibration was 5 seconds.

2-Body attached. Here the standing subjects were attached at hip-level to a back-support by means of a belt. Subjects attached in this way perceived whole-body illusory sensations of movement when vibrations were applied to ankle muscles. The movements were quantified by the subjects by means of a joystick, and a qualitative verbal description was recorded on tape. In this case, the vibration was applied for 10 seconds.
3-Reconstituted axial plantar pressure forces. Standing subjects were held in position by elastic braces which replicated almost the same axial sole pressure forces as those encountered in the normal gravity environment. The subjects' kinaesthetic sensations were analysed from the joystick and comments recordings, as under condition n°2. Test condition n°3 was run only on orbit. Here the vibration was applied for 10 seconds.

-Free-floating. Only one of the subjects (SA) was tested under this condition, where he was asked to float freely without touching the cabin walls, first in a fully extended position and then in a flexed position (with ankle, knee, and hip joints actively maintained at an angle of 90°). Here the vibration was maintained for 10 seconds.

Results

Muscle Proprioception and Postural Regulation

The contribution of sensory signals arising from muscle proprioceptive receptors to controlling erect posture was investigated in the present study by analysing whole-body motor responses to tendon vibration applied to the ankle muscles (tibialis anterior and soleus muscles, vibration-induced-falling: VIF). The amplitude and the kinematic characteristics of postural responses were recorded in the form of goniometric and kinesigraphic measurements (Figure 1, panel A) and leg muscle EMG activity measurements.

The postural sways of both subjects were found to occur in the backward direction when vibration was applied to the soleus muscles and in the forward direction when it was applied to the tibialis anterior muscles (Figure 1, panel A), as has been classically reported in the literature.

In general, the vibration-induced postural reactions were relatively homogeneous and presented a weak variability in the case of tibialis anterior stimulation, whereas they were characterized by an important scattering in the case of responses to soleus stimulation.

During the training and preflight periods, the postural sway amplitude gradually increased in one of the subjects (SA), reaching 20 cm at the level of the shoulder as shown by kinesigraphic recordings. In all cases, the postural changes observed consisted of a whole-body rotation around the ankle joint involving no change in the configuration of the body segments (Figure 2). For this reason we have used the displacement of the shoulder to measure the angular displacement of the body. In S3, the amplitude of the postural response to tibialis anterior vibration also increased, whereas in the case of soleus vibration it was found to decrease during this period. Generally speaking, the amplitude of the backward postural responses was greater than that of the forward ones (Figure 3).

The leg muscle EMG recordings showed the occurrence of compensatory muscle activity patterns involving the soleus and biceps femoris in the case of forward movements and the tibialis anterior and quadriceps femoris muscles in the case of backward movements. Tonic muscle activity was, moreover, observed to occur in the soleus muscles while the subjects were maintaining an erect posture before the vibratory stimulus was applied (Figure 4).

Inflight, the postural responses developed differently depending on whether the tibialis anterior of soleus muscles were vibrated. At first the response to tibialis anterior vibration either decreased sharply (SB) or disappeared altogether (SA), whereas the response to soleus vibration remained normal at the beginning of the flight, that is, 8th and 20th days (on FD8 and FD20) after launching in the case of SA and SB, respectively (Figure 2). On the 21st day (on FD21), the response amplitude decreased considerably in SA. As in the preflight tests, no change was found to occur in the angles formed by the various body segments during the postural reactions (Figure 3), apart from that of the ankle (inverted pendulum-like movement). In all cases, the kinematics of the vibration-induced postural responses were altered in microgravity: the speed of the subjects' body movements in particular decreased by about one-half.

At the EMG level, the compensatory mus-
Figure 1. (A) Postural responses induced by vibrating the distal tendon of the soleus (left) and tibialis anterior (right) muscles in a subject standing in an erect position with his eyes closed. The traces show the trajectories of markers placed at head, shoulder, hip, and knee levels. These trajectories were calculated from kinesigraphic recordings (VICON system). The vertical lines on the central part of the recordings give the vibration time (5 s at 70 Hz). (B) Illusory whole-body movements in the backward (left) and forward (right) direction induced by vibrating the tibialis anterior and soleus muscles, respectively, (for 10 s at 70 Hz). The subject was strapped to a restraining device and had his eyes closed. He was asked to use the joystick (the recordings of which are given below) to describe his experience of illusory body tilt.
Preflight Flight Postflight

Figure 2. Examples of kinesigraphic recordings of the postural movements induced by vibrating the tibialis anterior (top) or soleus (bottom) muscles (for 5 s at 70 Hz) of astronauts standing with their feet attached to a platform. The dots on each diagram represent the markers placed at head, shoulder, hip, knee, ankle, and foot level. The arrows show the direction of the postural movements. The recordings were made before, during, and after the spaceflight.

The kinaesthetic effect of the proprio muscular afferents elicited by vibrating the tibialis anterior or soleus muscles were investigated in subjects attached to a backrest. In this situation, subjects generally describe having illusory sensations of whole-body movement in the sagittal plane around the ankle joint (Figure 1B).

During the training and preflight periods, the two astronauts both reported having the feeling that their bodies were tilted backward when the tibialis anterior muscles were vibrated. During preflight tests, the amplitude of vibration, they can be said to resemble the classical tonic vibratory response (TVR) (Figures 4 and 5).

The application of axial loads by means of braces that reproduce plantar forces similar to those encountered on the earth provoked a deep suppression of the tonic activity of tibialis anteriors. The postural motor responses were absent in this condition.

Postflight, as early as 2 days after return to earth (R+2), the EMG and kinematic characteristics of SA's postural responses were comparable to those of the preflight data (Figure 2). The postflight postural reactions of SB, who spent 4 months on orbit, also recovered the characteristics typical of the normal gravity environment, as measured just before the flight (F-6).
Figure 3. Maximum amplitude of postural displacements induced by vibrating the tendons of tibialis anterior (top) or soleus (bottom) muscles of two astronauts standing with their feet attached to a platform. The amplitudes of the postural responses were recorded in the form of goniometric recordings (ankle angles) made before, during, and after the spaceflight.

of these illusory movements was relatively small and irregular, though larger in the case of tibialis anterior vibration, where the backward tilting sensation reached an average value of 25° 6 days before takeoff (F-6) in SA and 23° in SB. The forward tilting sensations induced by stimulating the soleus muscles had a low amplitude in the case of SA (maximum 15° 6 days before takeoff (in F-6) and a slightly larger amplitude in the case of SB (Figure 6).

The illusory sensations reported by SA in flight 8 days after launching (FD8) were similar to those he experienced preflight, although the average amplitude was greater on orbit in response to vibration of both the tibialis anterior and the soleus muscles (Figure 6). On the 21st day of the flight (FD21), a major change occurred in this subject: the tilting illusions previously induced by tibialis anterior vibration gave way to the feeling that the whole body was being raised from the floor. On the same day, stimulation of the soleus muscles no longer had any kinaesthetic effects.
Figure 4. Postural and electromyographic responses induced by applying vibration (for 5 s at 70 Hz) to tibialis anterior of an astronaut (SA) under normal gravity (right) and microgravity (left). From top to bottom, the traces are: goniometric recordings of the postural tilt, and integrated electromyographic recordings of the responses elicited in the biceps femoris, quadriceps femoris, soleus, and tibialis anterior muscles.

Figure 5. Postural and electromyographic responses induced by applying vibration (for 5 s at 70 Hz) to the soleus muscle in SA under normal gravity (right) and microgravity (left). From top to bottom, the traces are: goniometric recordings of the postural tilt, and integrated electromyographic recordings of the responses elicited in the biceps femoris, quadriceps femoris, soleus, and tibialis anterior muscles.
The same change occurred on the 20th day (FD20) in SB, who also felt as if he were being uplifted in response to tibialis anterior vibration (Figure 7). On the other hand, soleus vibration induced in this subject either forward body tilting or foot dorsiflexion sensations.

The perceptual illusions elicited in microgravity when braces were used to reproduce the missing axial plantar pressure forces were of a kind similar to those induced in the normal gravity environment in subjects attached to a backrest: these consisted therefore of
Vibration-induced postural illusions (70 Hz)

Figure 7. Diagram of the illusory body movements induced by vibrating the tibialis anterior muscles (for 5 s at 70 Hz). In an astronaut, attached to a restraining device with his eyes closed, vibration applied under normal gravity induced the feeling that he was tilting backwards (left), whereas the same stimulation applied under microgravity gave rise to the impression that he was being raised upwards (centre). When braces were used on orbit to replicate the lacking axial plantar pressure forces, this astronaut recovered the same sensations as previously under normal gravity (right).

Discussion

Studies of human adaptation to the space environment often entail a small number of subjects. This is the case of the present work, in which it was impossible to get a sufficient subject population to allow adequate statistical analysis of the results. Nevertheless, the preliminary results we present here lead us to some theoretical propositions that we will now discuss.

Numerous previous studies have shown that proprioceptive function is altered during exposure to microgravity environments (4,5,6,28,29,30). Weightlessness has also been shown to affect proprioception in studies using a wide range of experimental conditions (orbital flights with various durations, parabolic flight, immersion, and bedrest) and various methods of testing proprioceptive function (tendon and Hoffmann reflexes, vestibulospinal activation, psychophysical methods of testing position sense, analysis of perceptual illusions). The causes of these alterations have not yet been fully elucidated, and several hypotheses have been put forward, mainly suggesting that the decrease in the activity or excitability levels of the muscle or tendon receptors may be due either to changes in the biomechanical envi-
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ronment of the muscle receptors, resulting from the absence of gravitational pull, or to changes in the vestibular excitatory control exerted on the alpha or gamma motoneurons (4). It has also been frequently suggested that weightlessness may entail the need for an adaptive reorganization of the central messages arising from the efferent copy and the altered proprioceptive reafferents elicited by the actions performed in this type of environment (1,4,31). Moreover, it has been clearly demonstrated that visual cues play an important substitutive role (5,30) and that tactile messages, which are greatly altered in microgravity, also play a leading part in the spatial disorientation of the body.

Like most somesthetic information, muscle proprioceptive information undergoes a dual processing: first, a sensorimotor processing, which is largely automatic, occurs in the medullary or subcortical loops involved in the reflex processes controlling postural and body-segment motor activity; and secondly, a perceptual processing mediates the cortical elaboration of movement and position sense. This does not mean however that muscle proprioception is by any means the only modality responsible for body representation.

By using tendon vibration to experimentally manipulate the muscle proprioceptive pathway during a spaceflight, it was possible in the present study to investigate how proprioception functions and to describe how the sensorimotor and kinaesthetic processing of muscle spindle information adapt to the weightless situation.

The most noteworthy finding made during this spaceflight was that muscle proprioceptive function remains functional in weightlessness, since it was still possible to activate the muscle spindles by vibration and to induce motor responses and illusory sensations of movement. Only the characteristics of these responses change in microgravity, which indicates that adaptive sensorimotor and cognitive processes are gradually set up. Here it is proposed to discuss the following points: 1) inflight changes in the sensorimotor processing of proprioceptive signals arising from the ankle muscles; 2) changes in the central processing of these signals used for the coding of the spatial orientation of the body and its movements.

1. In Weightlessness, Did Ankle Muscle Proprioception Gradually Cease to Participate in the Control of Standing Posture?

Although forward and backward reflex postural responses still occurred on the 8th day of the spaceflight (FD8) in response to tibialis anterior and soleus vibration, respectively, by the 21st day (FD21) they had either disappeared altogether or decreased in amplitude and lengthened in duration. At the same time the compensatory EMG postural patterns recorded on Earth and at the beginning of the flight had also disappeared.

The disappearance of the vibration-induced postural responses was accompanied in the vibrated muscles by the development of a tonic EMG response resembling the classical TVR in its latency and duration (23,32,33). These TVR occurred both in the tibialis anterior, which are known to maintain their tonicity in weightlessness when the subject is standing (29) and in the soleus, which produce no tonic activity in weightlessness. The development of TVRs probably indicates that the monosynaptic and polysynaptic myotatic medullary loops have been activated, after increasing in gain with time during the spaceflight. This does not seem to be compatible with the changes in the tendon and Hoffmann reflexes, which have been reported to occur in microgravity after disappearing for the first 2 days. These reflexes seem to have been recovered at about the date at which vibration began in our experiment to induce TVRs in the ankle muscles (6,28,34,35,36). Nor does the potentiation of the Hoffmann reflexes described postflight after the return of Soviet and American astronauts seem to fit our TVR data, as these responses were no longer observed in our experiments in the postural muscles after return to Earth.

Another explanation for the increase in the
excitability of the myotatic loop which occurred late in the flight might be that it resulted from changes in the influences of vestibular origin exerted on the spinal alpha and/or gamma motoneurons. The changes affecting vestibulospinal reactivity in weightlessness were thoroughly documented in the Canadian experiments carried out during the first Spacelab and D1 spaceflights, using the Hoffmann reflex method and analysis of the EMG responses to free falling or to sudden changes in the planar support conditions (6,8,37,38). The results of these experiments showed, in particular, that the vestibulospinal reflexes decrease with time during spaceflight; this decrease was particularly marked in terms of the EMG responses to free falling or artificial acceleration during spaceflight. The vestibular excitability was rapidly recovered, moreover, in most of the subjects on their return to Earth. The above explanation is not very convincing, however, since the postural responses to vibration were still present on the 8th day of the flight (FD8), whereas the gravitational forces acting on the otolith system began to disappear as soon as the subject was on orbit. The changes in the vestibulospinal interactions were therefore probably not responsible for the disappearance of the vibration-induced postural responses in the later stages of the flight or for the fact that they were replaced by more local reflex responses. On the other hand, it has been established that the motor responses induced by vibration are liable to affect not only the vibrated muscle, but also its antagonists and even more distal muscles whenever the behavioural context changes (23,27,39,40), and that the excitability of the reflex loops can vary considerably depending on the subject’s awareness of the risk of postural destabilization in a given contextual situation (Berthoz, personal communication, 1974).

On the basis of the latter data, which show the adaptive contextual flexibility of the links between sensory signals and motor structures, it is possible that the proprioceptive information arising from the ankle muscles may be re-assigned during spaceflight, from whole-body postural control to the motor control of the feet alone. In fact, this information no longer has any adaptive functional relevance in weightlessness, where the feet no longer play a postural role and the body balance is no longer threatened by gravity. The changes in question might therefore reflect not so much a major change in the spindle proprioceptive receptor function but rather indicate a more central sensorimotor rearrangement organized by the CNS so that from the same sensory input new motor responses can be built up that will be more appropriate for dealing with the new gravity environment. It can thus be suggested that muscle proprioceptive information does continue to play a sensorimotor regulative role in weightlessness, and that this role gradually adapts to the new behavioural requirements.

2. Muscle Proprioception Continues to Provide a Reference Frame for Body Posture and Movement in Microgravity

Although muscle proprioception continues to provide a reference frame for body posture and movement in microgravity, it undergoes a functional reorganization as new motor skills are learned during exposure to the weightless environment. This is the main finding that emerges from our study of the illusory body movements induced by ankle muscle vibration. Previous authors investigating the kinaesthetic changes in proprioceptive function occurring during spaceflight or parabolic flight have reported that the crewmembers’ awareness of their own body or limb positions deteriorated considerably when they were unable to use visual control (5,29), and that they were subject to proprioceptive illusions which made it difficult for them to distinguish between movements of their own bodies and those of the external surroundings both in flight and immediately after their return from microgravity (4,41). Similar illusions were reported during phase 2G of parabolic flights (3). Lackner’s data (42) and preliminary data of our own (Deshays and Roll, 1988, unpublished
data) both show that the characteristics of vibration-induced illusions change considerably throughout the various phases of parabolic flight. The data obtained during parabolic flight contrast sharply with the results of our spaceflight experiments in which the illusory body-movements induced by vibrating the ankle muscles were used to investigate the kinesthetic role of muscle proprioception. In fact, these illusory whole-body movements continued and were even facilitated (soleus vibration) in weightlessness. This discrepancy suggests that a transient exposure to weightlessness (20 seconds) does not have the same consequences for the sensory systems or for the central processing of sensory information as the consistent, durable exposure to 0G which is encountered during orbital spaceflight.

After some time in weightlessness, new illusory body uplift and foot flexion sensations, therefore, emerged in response to ankle muscle vibration. The CNS can therefore be said to have begun to re-interpret muscle proprioceptive messages arising from the ankle muscles after long exposure to weightlessness. The sensory messages that serve on Earth to code antero-posterior body movements in standing subjects seem here to have been re-assigned to the kinesthetic coding of whole body axial transportation or foot movement. This transformation seems in our opinion to reflect a central reinterpretation of the sensory signals relating to the learning of new motor strategies appropriate to microgravity rather than a change in the proprioceptive peripheral sensory input. It has been recently shown that proprioceptive signals coding body posture cannot be immediately re-interpretated by the CNS. Yet, it is possible to immediately re-interpret sensory data whenever they are accompanied by other data normally associated with a particular context (27,45,46). Processes of this kind may, of course, coexist with other slower mechanisms that serve to build up a new reference frame for coping with the microgravity environment. On these lines, it is worth
mentioning the fact that postural illusions affecting the lower limbs have been reported to last several days after return (47) and to result in postural disturbances that disappeared only several days after the end of the flight (2,29, 37,48-50).

In conclusion, our results suggest that no changes attributable to peripheral receptor impairments were observed in the present analysis of the sensorimotor and representational aspects of muscle proprioceptive function during a long spaceflight. It emerges, however, that a possible reorganization of the motor and perceptual processing of muscle proprioceptive information took place during this flight.

More specifically, the muscle discharges arising from the ankle seemed to gradually cease to mediate the control of standing posture and to switch over to the local reflex control of foot motor activity alone.

The kinaesthetic function of this information was also gradually reorganized during exposure to weightlessness, since illusory whole-body movements in the three dimensions of space began to be coded instead of the previous illusory anteroposterior movements.

Our study of illusory movements induced by vibration furthermore showed the occurrence of instantaneous adaptations of the sensory information processing cooperating with the longer multisensory recalibrations induced by exposure to weightlessness.

The last point worth mentioning is that this perceptuomotor reorganization of muscle proprioceptive function seems to reflect the learning of the new motor skills required to cope with the weightless situation: in particular, the feet acquire a new propulsive function and new behaviour has to be learned involving the occupation of the third dimension of space. This motor reorganization may result in new interpretations being given by the CNS to sensory messages of proprioceptive origin as part of the adaptation of the subjects’ responses to this unusual type of environment.

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