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Adaptive modifications of postural attitude in conditions of weightlessness

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Summary. Adaptation of static posture was studied before, during, and after a 7-day space flight. Body segment orientations, body stability, and muscle activity underlying the reproduction of several postural attitudes were examined in various visual situations either with the shoes attached to the floor or during free floating. In standing or relaxed subjects whose shoes were attached to the floor, the tonic activity of the ankle flexor was enhanced relative to that in the same posture on earth, whereas the extensor activity disappeared. Errors in attempting to reproduce the normal terrestrial upright posture and a forward-leaning posture were accompanied by major changes in the synergies between neck, hip, knee, and ankle joints. These changes are mainly attributed to cumulative adjustments in response to nonvestibular signals such as tactile, articular, and proprioceptive cues.

Key words: Posture – Adaptation – Vision – Weightlessness – Man

Introduction

In hypokinesia experiments in which subjects were immersed in water to simulate the elimination of weight load in space flight (Graveline et al. 1961; Mitarai et al. 1978; Kozlovskaya et al. 1983) and from data obtained after short-term (Homick and Reschke 1977; Young et al. 1984) and long-term (Kozlovskaya et al. 1983) space flight, subjects displayed: 1) acute alteration of the control of posture and locomotion, especially in the absence of normal visual cues; 2) proprioceptive hyperactivity; and 3) profound disturbance of the accuracy of precise voluntary movements. These ataxic disorders were often associated with changes in muscle properties which depended on the duration of the immersion or weightlessness.

An explanation for such disturbances in sensorimotor systems may lie in changes in the neural information received from mechanoreceptors (Von Baumgarten et al. 1981; Clément and Droulez 1983), particularly from the utricle and saccule (Graybiel and Kellogg 1967; Homick et al. 1977). It has also been postulated that vision, which plays an important role in the control of posture (Dichgans et al. 1972; Lestienne et al. 1977; Nashner and Berthoz 1978), could provide substitute information for the correction of the central sensorimotor programs during exposure to weightlessness (Lestienne and Droulez 1983). The increase of visual dependance in zero G might therefore be the cause of the dramatic post-flight instability in the absence of vision (Kenyon and Young 1986).

In previous studies (Clément et al. 1984, 1985) we demonstrated that in conditions of weightlessness, transient postural corrections associated with voluntary arm movement and elevation on tiptoe or an unexpected shift of the foot support were comparable to those observed before the flight. Postural resistance or tone, which is maintained primarily by tonic contraction of the flexor muscles was considerably reduced. Furthermore, the body leaned forward exaggeratedly when the astronauts were in darkness or were restricted to central vision. These findings led us to assume that the changes in the sensory inputs selectively altered certain components in the sensorimotor system, specifically the tonic muscular activity. We could not explain why these changes did not induce postural instability even though the whole-body orientation was clearly affected.

As the earlier studies were of only two astronauts, and as observations about posture in space are

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extremely rare (Thornton and Rummel 1977), we have now systematically studied two more astronauts during a 7-day space flight to discover the relative orientations of the various segments of the body and the postural muscle activity underlying the reproduction of postural attitudes learned on earth. We paid special attention to visual and tactile information to document how these two sensory modes affect posture in conditions of weightlessness. The experiments reported here are parts of the "Equilibrium and Vertigo" experiment performed aboard the US space shuttle "Discovery" in June 1985 (STS 51-G).

Methods

1. Subjects and test schedule

The study was carried out before, during, and after the 7-day space flight of two astronauts, here called "A" and "B". The subjects were tested three times before the flight (on days F-30, F-5, and F-4). The postflight tests took place less than an hour after landing (R), and one day (R + 1) and three days (R + 3) later. The preflight and postflight tests were carried out in the NASA Johnson Space Center (Houston, Texas) and in the NASA Dryden Flight Research Facility (Edwards Air Force Base, California) under the supervision of the authors. Flight days were numbered FD1 to FD7.

Testing during the flight took place every day for subject A, starting 6 h after the launch, and only on FD2, FD4, and FD7 for subject B. However, following the recommendations of the astronauts during the postflight debriefing, we decided to discard some data from subject B on FD7. Astronaut A was trained to perform the test procedure and to manipulate the apparatus 5 months before the flight, and astronaut B only a month beforehand.

2. Procedure

The subjects stood erect, with their shoes attached to the floor. They were instructed to maintain a normal terrestrial standing posture (U, or "upright", posture), or to lean forward by about 4° (F posture). In both postures, three different visual situations were tested: normal vision, occluded vision, and stabilized vision. Goggles were used to occlude the vision or to stabilize the visual surroundings. For the latter purpose a 30-cm-long box was attached to the goggles in order to minimize vergence of the eyes. This box was illuminated, and the inside was covered with a checkerboard pattern. Subjects were asked to fix their gaze on a point at the far end of the box.

For each of these six experimental conditions, the subjects were asked to maintain a fairly stable posture for 80 s. In addition to these experimental situations, the postures of the two astronauts were recorded when completely relaxed, both with the shoes attached to the floor and also when free-floating without any tactile contact.

3. Recording techniques

To save time and for ease of operation, we needed compact, portable equipment that could be used without the help of a crew member. We choose a purpose-built device, called Pocket[1]. This consisted of three modules attached to a belt at the subject's hip level: a battery pack, an electronic control box, and a digital tape recorder. The parameters recorded were electromyographic (EMG) signals of two muscles acting on the ankle joint: the Tibialis Anterior (TA) and the Soleus (S). The pregelled disposable surface EMG electrodes were placed 2 cm apart over the belly of the TA and of the S on the right leg. A reference electrode was placed just under the knee. The skin was cleaned with alcohol and slightly scratched with a piece of Velcro rough nylon fabric at the point where the EMG electrodes were stuck. The EMG signals were amplified (gain 2500) and fullwave-rectified and bandpass-filtered (3–95 Hz) before recording. The angular displacement of the ankle joint in the sagittal plane was measured with a lightweight adjustable potentiometer. The range of the angular ankle motion was 20° in both directions, with a linearity of 1%. EMG signals and ankle angular displacement were sampled at 5.12 and 10.24 ms, respectively.

In addition to this Pocket equipment, a camera recorded the positions of the various body segments in the sagittal plane. Small circular markers (2 cm in diameter) were placed on the head, shoulder, elbow, hand, hip, knee, and ankle. The two-dimensional locations of the markers were graphically analyzed from the pictures for reconstruction of the posture. The mean value and the standard deviation of each joint position was calculated from five successive images taken at 15 s intervals.

Results

1. Influence of postural task

Compared to the posture on the ground, the neck, hip, and knee were flexed significantly more while attempting to maintain a normal terrestrial standing posture in weightless conditions (U posture) (Fig. 1). These effects were greater in subject B. However, the data for subject A, who performed the experiment daily in flight, allow a more precise description of the pattern of change in the positions of these joints throughout the flight. The ventriflexion of the neck seen at the beginning of the flight gradually decreased, returning to close to its preflight value by FD6 and FD7, while the knee and hip flexion increased after FD4. The ankle dorsiflexion also slightly increased after FD3. Considerable flexion of the neck was observed for 48 h after the landing.

On earth before the flight, when the subjects were instructed to lean forward to the F posture from the normal U posture, mean changes ($\Delta\Theta$) in the whole-body tilt were 4.5° and 3.5° for astronauts A and B, respectively. In weightlessness, these changes were about twofold and fourfold greater respectively at the beginning of the flight (Fig. 2). $\Delta\Theta$ then rose to a peak on FD4 (B) or FD5 (A), and then decreased for subject A by FD7.

1 Designed and built by F.X. Sené, P. Simon and G. Petit, EREMS, Toulouse, France

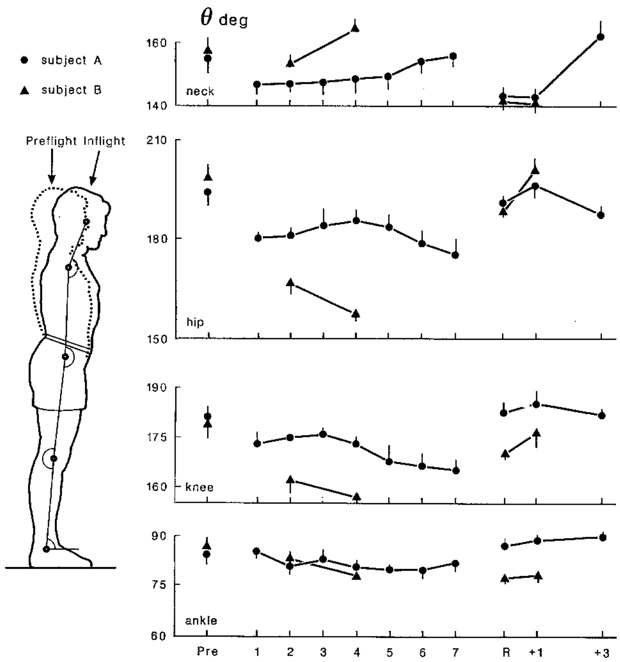

Fig. 1. Positions (Θ) of the neck, hip, knee, and ankle joints of astronauts A and B attempting to maintain an upright posture with the shoes attached to a support during preflight tests (Pre), in conditions of weightlessness and normal vision from flight days 1 to 7, and during postflight tests an hour after landing (R), and one day (+1) and three days later (+3). Note the difference in the positions of the trunk and the head between preflight and early inflight measurements on the schematic representation shown on the left part of the figure

The pattern of change in the multijoint synergies during the shift from posture U to F is illustrated at the right in Fig. 2. This shift was accomplished by an ankle dorsiflexion of amplitude similar to that observed before the flight for subject A, and four times larger for subject B. Whereas on earth the ankle dorsiflexion was accompanied by a slight flexion of the knee and extension of the hip, in weightlessness this synergy was reversed and amplified through at least FD4. To maintain the F posture in one G, subject B flexed the neck far more than subject A. In zero G, however, neck extension partially compensated for the exaggerated forward tilt, at least on FD2 for subject B. Early postflight measurements showed two extreme synergies during the transition between U and F postures: an "extension" synergy of the neck, hip, and knee joints in subject A, and conversely a "flexion" synergy of the neck, knee, and ankle in subject B.

Postural instability in the U and F postures is compared in Fig. 3, which gives the power spectra of the frequencies of the angular displacements of the ankle for subject A. The amplitude of the ankle sway in the U posture was roughly the same at the beginning of the flight as in the preflight tests for all frequencies. An abrupt decrease of this amplitude was observed after FD4. It is important to remember that changes in multijoint synergies were observed in the same period. In the F posture the amplitude of ankle sway was considerably reduced after FD1 for

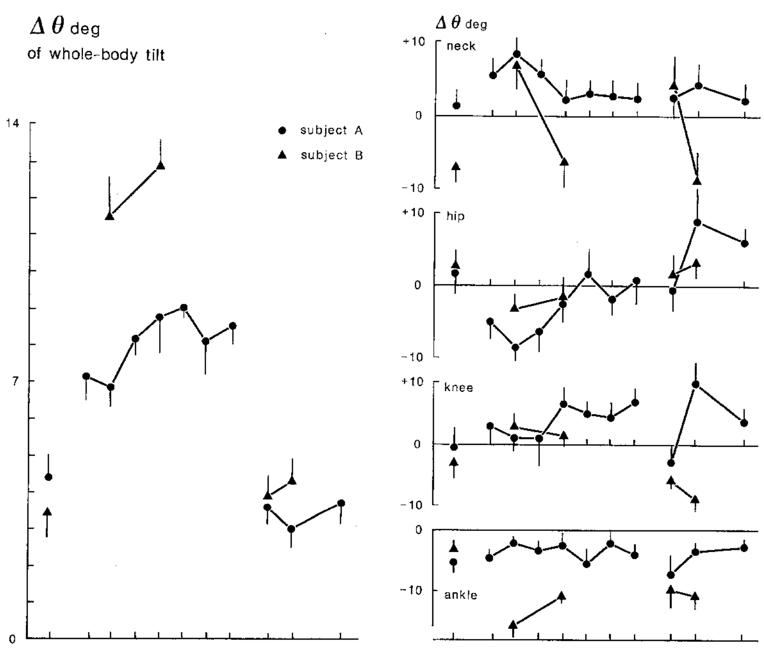

Fig. 2. Pattern of mean change (ΔΘ) in the whole-body tilt (left) and in the positions of various joints (right) when astronauts went from the upright posture to the forward-leaning posture throughout the flight

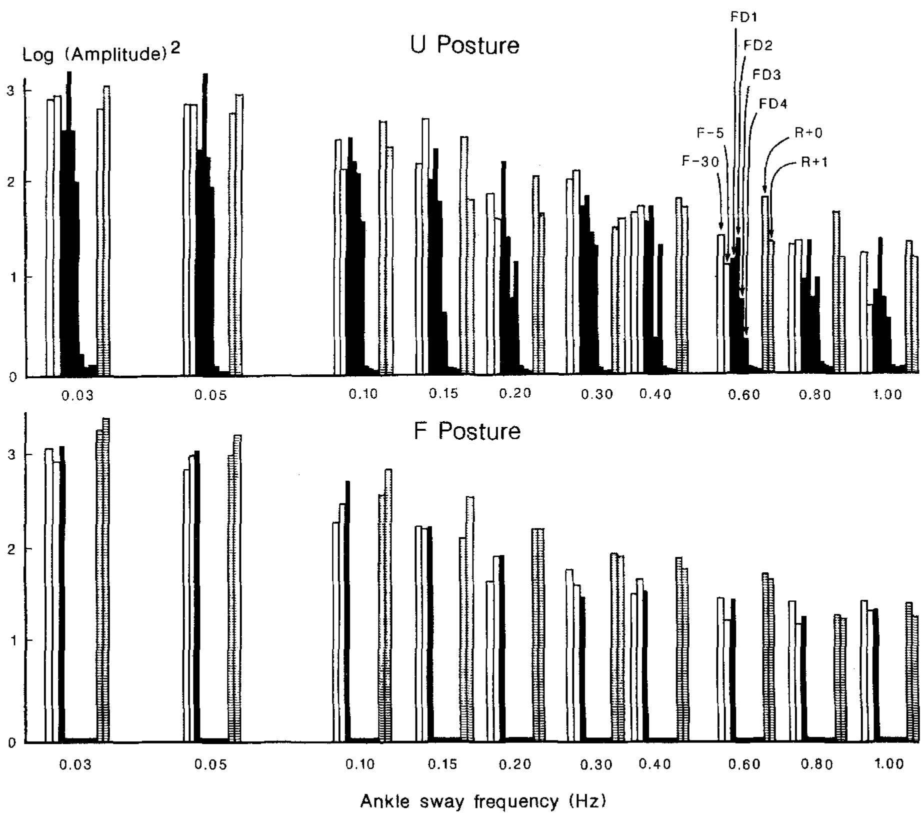

Fig. 3. Fourier power spectra of anterior-posterior ankle sway of subject A in the upright (U) posture and in the forward-leaning (F) posture, before (F-30, F-5), during (FD1 to FD7), and after (R + 0, R + 1) the space flight

all frequencies. These results would suggest that there is a relationship between the changes in erect posture and the absence of measurable ankle sway. After the landing the instability was similar to or slightly larger than that measured before the flight. Similar results were obtained for subject B.

2. *Influence of visual and tactile cues*

The influence of vision on static posture was evaluated by calculating the difference ($\Delta\Theta$) between the body tilt in normal vision and that in stabilized vision. Vision had more influence on subject B than on subject A through at least FD4 (Fig. 4). Stabilized vision induced a gradual forward shift of the entire body of subject A in the course of the flight. For both postures there was a plateau from FD5. However, $\Delta\Theta$ was significantly smaller in the F posture for this particular subject. On FD1 in the U posture, the absolute mean value of the body tilt of subject B with stabilized vision was about 28° with respect to the perpendicular to the support to which his shoes were attached (the corresponding value for subject A was about 8°). This amplitude was not reached spontaneously as soon as the subject's vision was stabilized, but rather the body gradually leaned forward in the course of the recording sequence. Postflight measurements seemed to show a gradual return to the preflight baseline values, especially for subject A.

The parameter $\Delta\Theta$, calculated for each body segment separately in the U posture, is reported on the right in Fig. 4. For both subjects the forward tilt in stabilized vision was accomplished by dorsiflexion of the ankle and variable flexion of the knee. At the beginning of the flight in subject A, these two flexions were partially compensated for a concomitant extension of the neck and the hip joints. This compensatory synergy progressively disappeared and presumably causes the whole-body forward tilt in stabilized vision. In subject B, on the other hand, the exaggerated forward tilt was mainly due to a very large ankle dorsiflexion together with a marked hip flexion, whereas the knee and the neck were not affected by stabilized vision. The drastic decrease of $\Delta\Theta$ described previously was thus due to a decrease of the ankle dorsiflexion and of the hip flexion.

3. *Postural muscular activity*

To obtain a quantitative estimate of the level of tonic EMG activity of both the S and the TA muscles for a given situation, the integrated EMG activity (Q) was

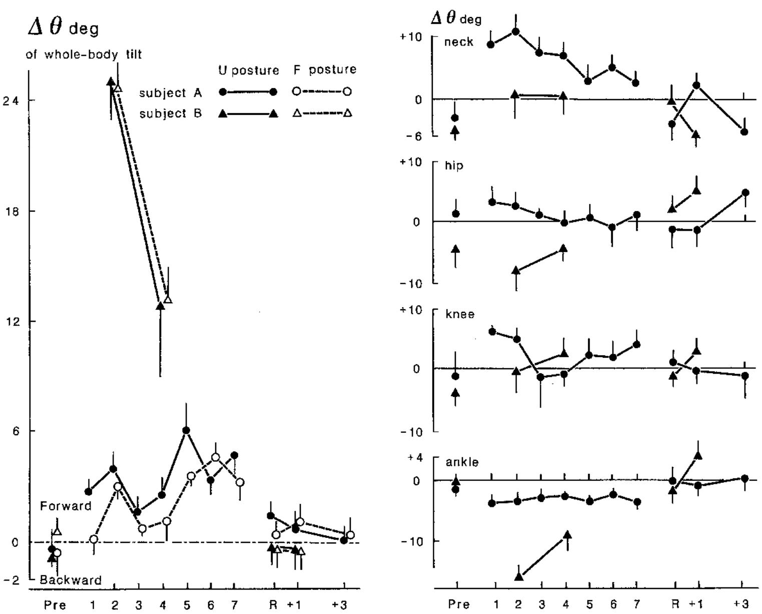

Fig. 4. Pattern of mean change (ΔΘ) in the whole-body tilt (left) of astronauts A and B between situations of normal vision and stabilized vision in both the U and F postures, and mean change in the positions of various joints (right) in the U posture, throughout the space flight

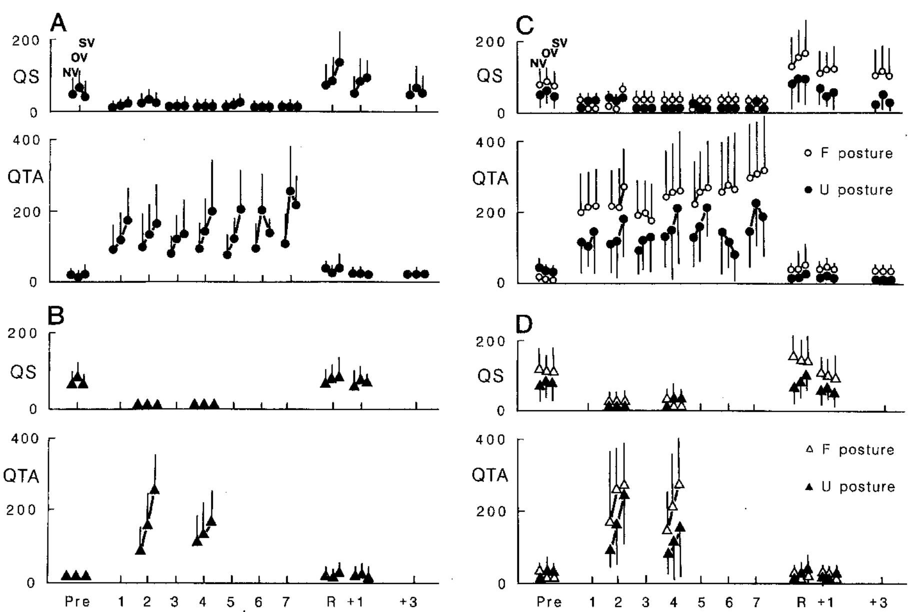

Fig. 5. A, B Tonic EMG activity of the Soleus (QS) and the Tibialis anterior (QTA) muscles integrated during 80 s in the U posture for subjects A (**A**) and B (**B**). **B, C** Same parameters integrated during 5 s before (U posture) and 75 s after (F posture) the voluntary forward body tilt for subjects A (**C**) and B (**D**)

calculated for each experimental sequence. On earth, in the U posture, we found the typical tonic EMG distribution between extensor and flexor: a very low value of QTA (i.e. for the flexor muscle) and a high value of QS (for the extensor muscle) (Fig. 5A, B). Changes in the visual situations induced only slight changes in the QTA and the QS values in both subjects preflight, but significant enhancement of the QS just after landing. In the U posture, inflight QTA was 5 to 15 times as high as the QS, depending upon the subject and the visual situation. In normal vision, the QTA values for subject A did not change significantly during the flight (Fig. 5A), whereas for subject B they decreased significantly from FD2 to FD4 (Fig. 5B). In stabilized vision, at least relative to normal vision, a significant increase of QTA was observed in flight in both subjects.

Figure 5C and D shows the QS and QTA values obtained for the two subjects A and B respectively, 5 s before and 75 s after the shift from the U to the F posture. The resultant previously described increase of the body tilt was accompanied by a significant increase of QTA, which was found consistently throughout the flight for subject A. The influence of

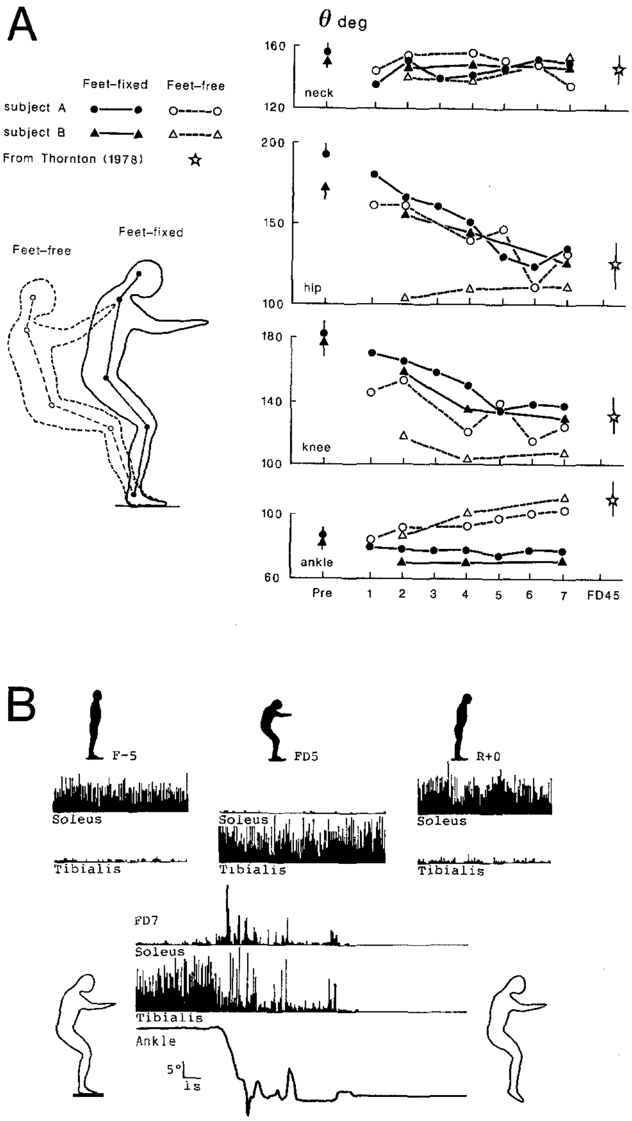

Fig. 6. A Positions (Θ) of the neck, hip, knee, and ankle joints in a relaxed posture in conditions of weightlessness (FD1 to FD7), either with the shoes fixed to the floor (feet-fixed) or with the subjects free floating (feet-free). Stars depict the mean data obtained by Thornton (1978) in free-floating subjects during the Skylab-4 mission. **B** Typical recordings of EMG activity of Soleus and Tibialis anterior muscles in the normal posture on earth before (F-5) and after (R) the flight, and in a relaxed posture with the shoes fixed to the floor in conditions of weightlessness (FD5), and during the transition to free-floating (FD7)

changed visual situations on this subject was not so pronounced in the F posture as in the U posture (Fig. 5C). The overall postflight QS values for this subject were demonstrably higher than the preflight values, and in the F posture this difference was still present at R + 3. For subject B the enhancement of the tonic activity in the TA was not so marked as for subject A at the beginning of the flight, though the whole-body tilt was about twice that of subject A. However, on FD4, a significant difference of the QTA values was observed between the U and the F posture (Fig. 5D). This finding could be explained by the fact that on FD2 the U posture induced a very high level of tonic activity in the TA, equivalent to saturation of the motor activity of this flexor muscle.

Figure 6A depicts the pattern of change in the positions of the neck, hip, knee, and ankle in a relaxed posture, either with the shoes fixed to the floor or with the subject free-floating. In the first condition all joints were flexed more and more except the ankle joint, whose dorsiflexion remained close to its ground-based value. During free floating, the hip was flexed more and the ankle went into plantar flexion. On FD7 the ankle angle, and also the angles of the other joints, were similar to the mean values calculated by Thornton (1978) for three subjects on pictures taken from FD8 to FD54 of the Skylab-4 mission. In the transition from the feet-fixed condition to a free-floating condition, the EMG activity completely disappeared from both the TA and the S muscles, and the ankle joint was plantar-flexed (Fig. 6B). However, we were surprised to find that in both subjects a relaxed posture with the shoes attached produced a tonic TA activity similar to that in the U posture. In a relaxed posture with the shoes attached to a support, as in the U posture, the high level of QTA persisted throughout the flight.

Discussion

The principal results presented here offer insights into the regulation of human body orientation and postural stability in an unusual environment such as weightless conditions. Exposure to orbital weightlessness dramatically modifies the otolith cues in conjunction with the semicircular canals (Graybiel et al. 1977). In orbital flight the gravitational and inertial forces acting on the otolith organs are close to zero. The absence of a constant force as a fundamental reference for determining the orientation of the head appears to hamper severely the ability of the central nervous system to carry out body orientation and postural control tasks. It is still widely believed that perceptual and coordination disorders in weightlessness are mainly due to effects on the vestibular system. However, we now feel that these disorders could be also attributed to the absence of axial force and static torques in the joints, and to the consequent cumulative alteration of nonvestibular signals such as tactile, articular, and proprioceptive cues.

Vestibular influences

Our results, in both the present and previous research (Clément et al. 1984, 1985), show that the level of the tonic activity of flexor and extensor muscles of the ankle joint changed considerably in subjects who were standing in conditions of weightlessness. The tonic activity of the TA was profoundly enhanced while that of the S disappeared when the subject was standing quietly. We had suggested that these findings could be interpreted as a manifestation of a functional, reversible deafferentation of the otolithic system. Indeed, pioneering experiments of Magnus (1926) on deafferented animals suggested that deafferentation of the otolithic system would produce a change in the excitability of the motoneuron pool, achieved by suppression of the factor that excites extensor muscles and release of the factor that inhibits flexor muscles. Another argument in favor of this interpretation is the observation of changes in the otolithic peripheral end-organ of the frog during orbiting experiments (Gualtierotti 1972). Furthermore, recent studies performed during the Spacelab-1 flight revealed a dramatic decrease of the amplitude of the H reflex (Reschke et al. 1986) and of the direct vestibulospinal responses recorded on the soleus (Young et al. 1984), findings which are in accord with our previous data about reduction of the long-latency stretch reflex in weightlessness (Clément et al. 1985). Indeed, other authors (Elner et al. 1976) have already suggested that the vestibular system participates in these fast responses of postural muscles, presumably through the mediation of supraspinal centers (Melvill Jones and Watt 1971).

Mechanical influences

A different interpretation is possible, however. The resting position of the ankle due to the passive elastic force of the two pairs of antagonist muscles, as evaluated in the free-floating situation, is at an angle of about 100° according to our data. In a subject standing upright in weightless conditions with the shoes attached to a support, this angle was near 80°. In this latter situation the flexor muscle had to be activated to counteract the moment of the passive forces exerted by the extensor muscle. This interpretation is consistent with the EMG activity recordings. Indeed, an increase of the ankle dorsiflexion observed during the F posture or the U posture in different visual situations was closely correlated with an increase of the tonic muscular activity of the ankle flexor muscle. A recent investigation performed during parabolic flight showed that the redistribution of the EMG activity between the S and the TA takes place after several seconds of weightlessness (Clément and André-Deshays 1987). Furthermore, the same authors reported that in a subject standing with the shoes attached to the floor, the EMG activity of the flexor muscle decreased as the ankle moved passively backwards. EMG activity was absent for an angular position of the ankle close to that observed in the free-floating situation. This plantar flexion of the ankle is presumably related to the resting position of this joint.

Tactile and proprioceptive influences

One might expect to find the same angular position when the subject, with the shoes attached, was asked to relax. However, our results clearly demonstrate that, in this last situation, the ankle adopted a dorsiflexion associated with a high level of tonic EMG activity on the extensor muscle. It is tempting to regard this dorsiflexion of the ankle as an automatic or reflex reaction produced by continuous tactile feedback from mechanical deformation of the skin of the foot during the activation of the flexor muscle. Indeed, the activation of the flexor necessary to bring the body upright would induce reaction forces exerted between the feet and the point of contact with the floor. The progressive forward body shift observed in subject B during an 80-s experimental session may have been the consequence of a sequential stimulation of tactile receptors. These receptors, stimulated more actively in the F posture, would then contribute to better stability. The progressive shift might also be due to the fact that the continuous feedback loop is acting very slowly till the reference value is reached.

Visual influences

As a whole, the maintenance of posture at the beginning of the flight would depend on the best use of tactile, articular, proprioceptive and visual information. In normal vision, abnormalities of standing posture, such as the relative positions of the body segments, would be the consequence of inadequate calibration of other receptors. In the absence of vision, these abnormalities are amplified. However, the control system would indirectly stimulate the other receptors to gain more information. The resultant posture would then be the one which gave the correct feedback to tactile, articular, and proprioceptive receptors. This suggests that adaptation to outer space is partially a learning process, in which the brain has to reinterpret the new pattern of multisensory information (Von Baumgarten 1986).

In terrestrial conditions the positions of the various joints which govern the posture of standing human subjects are organized by certain combinations of relative positions of the various body segments (Nashner and McCollum 1985). The limitations are mainly due to the narrow biomechanical boundaries within which it is possible to correct equilibrium by repositioning the center of body mass over a fixed base of support. The lower limbs could be regarded as levers for regulating the position of the trunk, which is the main object of regulation in the maintenance of upright posture (Gurfinkel et al. 1976, 1981). In weightlessness, because of the absence of gravity-generated axial force and static torques in the joints, the "unbolting" of the body kinematic chain permits a wider variety of postural attitudes. However, our results are in accord with recent concepts of postural control, namely that the performance of different postural tasks requires knowledge of the state of many parameters which cannot be signalled directly by specific receptors, such as segment length and configuration of the support surface and muscular torques, and are inferred from a predictive body state (Gurfinkel and Levik 1978; Nashner and McCollum 1985; Droulez et al. 1986; Lestienne and Gurfinkel 1988).

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