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Analysis of Posture and Eye Movement Responses to Coriolis Stimulation Under 1 G and Microgravity Conditions

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To detect the effect of microgravity on vestibular responses, we conducted Coriolis stimulation experiments at 1 G and μ G.
Five men with vision occluded were asked to tilt their head forward while rotating at 100 degrees/sec. Postural changes were recorded by a 3D linear accelerometer, and the distance of upper body movement was derived from recordings of linear acceleration. Eye movements were recorded by a CCD camera.
For a second period after commencing head tilt, the upper body moved 10 cm in the direction of inertia input at 1 G, but it moved to the opposite direction at μ G, i.e., 4 cm in the direction of inertia force. Nystagmus peak slow-phase velocity immediately after head tilt and its attenuation process did not differ between 1 G and μ G. The strength of movement sensation and the severity of motion sickness were far weaker at μ G than at 1 G.
It was concluded that inertia input is valid to induce postural and sensation responses only when the external reference is given Z axis by gravity. Vestibular ocular response may be maintained at μ G because the head reference is valid even after the external reference becomes arbitrary.

Key words: vestibulo-ocular reflex (VOR), coriolis stimulation, spatial orientation, parabolic flight

INTRODUCTION

In the course of day-to-day activities, we are able to walk and run through a given space without any loss of body balance. If you stop suddenly while running at full speed, although your body axis will tilt backward for an instant, you will remain standing upright without experiencing any deceleration. However, if you are in a vehicle which comes to a sudden stop, you will experience deceleration that makes standing unstable. When the spatial orientation is impaired in terms of vision, significant imbalance will ensue even in a healthy person [1-3]. To date, there have been no published reports providing a consistent explanation for these dynamic changes of posture and movement sensation [4]. To examine differences between active and passive control, we investigated the influence of Coriolis stimulation (head tilt while rotating) on standing posture and eye movement [5, 6].

With the subject's vision occluded, Coriolis stimulation induced shifts of the center of pressure and nystagmus consistent with inertia input from the vestibular apparatus. In contrast, with subjects viewing the interior of a room, stable standing posture and gaze (optokinetic nystagmus) were recorded [6]. These findings were consistent with the vectorial sum of visually-perceived external movement in the head and the inertia input. The differences in movement sensations could be similarly explained. From the results of these experiments, it was concluded that if the vectorial sum replicates the stationary external environment, stable control and natural movement sensation are produced. In contrast, if a stationary external environment is not replicated in the brain, ataxic control and passive movement sensation are produced. This mechanism can explain standing- and walking ataxia induced by visually-induced motion sickness [1-3].

We suppose that this vectorial sum uniformly controls posture and eye movement through the cerebello-vestibular pathway, and is projected to the higher cortex to produce motion sensation. At 1 G, gravity determines the Z axis of 3D coordinates which give the vectorial sum a reference for motion information. However, under μ G conditions, the vectorial sum loses its reference to produce information. If the hypothesis is correct, the response to the inertia input will disappear or markedly decrease at μ G. Numerous observations and experiments that have been reported in space do not contradict this possibility [7-12], but nor do they verify it. To test our hypothesis, we implemented the same Coriolis stimulation experiment at 1 G and μ G, and investigated the differences in vestibular reactions [13]. In this paper, we analyzed the responses under both conditions, and found interesting information that sheds some light on the mechanisms of posture control.

METHOD

1. Subjects

We recruited volunteers from within the university and explained the purpose of the experiment, as well as the methods, and all volunteers were made aware

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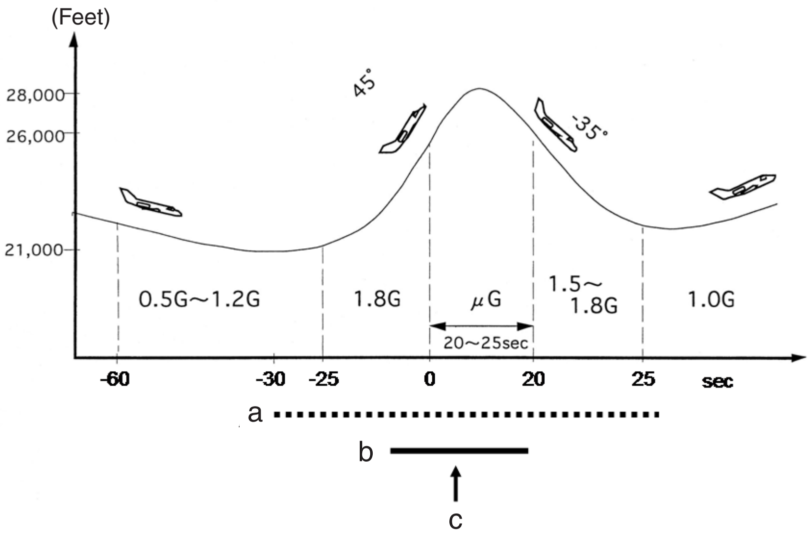

Fig. 1 Time lapse during aircraft experiments. Thirty seconds before moving into μ G, the subject is seated in a rotating chair (a), 10 seconds before moving into μ G, chair rotation is started (b). Five seconds after moving into μ G, the subject bends forward (c), and 20 seconds after moving into μ G, the chair rotation is stopped.

of the risk of unpleasant symptoms during the experiment. The study was conducted in five healthy adult males aged between 20 and 24 years, from whom consent was obtained. We presented our plans to the Tokai University ethical committee and to the National Space Development Agency of Japan (NASDA) ethical committee, and upon receiving their permission, we proceeded with our experiment.

2. Experimental apparatus

Rotation device:

As this device had to be loaded onto an aircraft, we considered such factors as weight, energy consumption, onboard aircraft space, and aircraft safety regulations, then proceeded to design and manufacture the rotation device (Nagashima Medical Instruments Co. Ltd., Tokyo). To meet loading requirements for the designated aircraft (the Grumman Gulfstream II, owned by Diamond Air Service Inc., Nagoya), the device was manufactured to the following dimensions: length 173 cm, width 100 cm, and height 172 cm. A small high-torque electric motor and drive belt were attached to the top of a square aluminum frame. A lightweight chair was suspended on the revolving shaft at the center of the frame using a universal joint. To prevent sway, the bottom center of the chair was fixed to the floor with a short cable. Rotating speeds were determined at 50, 100 and 150 degrees/second.

Recording body movement:

To record postural changes, we attached a miniature (20 x 30 x 16 mm) 3D linear acceleration sensor (Anima Corporation, Tokyo) to the breast region of each subject. After amplifying the acceleration of the left-right, forward-backward, and up-down linear movement components, the information was output from the device via the slip ring, and the maximum range of ± 2 g was captured by a laptop computer for each direction every 10 msec. Before recording, the gravitational direction was made to coincide with the sensor Z axis. To monitor the angle of head tilt, a belt-shaped angle sensor (Anima Corporation, Tokyo) was attached to the side of the subject's head, extending to the shoulder, and the angle of tilt at the time of ante flexion was recorded. On the same screen, an indicator was displayed when the head tilt angle reached 40° or more.

Recording eye movement:

Goggles installed with an infrared CCD camera on one eye, and which masked the other eye, were attached to the subject's head. Experiments were done with vision occluded. The video image signal of eye movements was output from the device via a slip ring, and was simultaneously recorded to tape and displayed on the monitor screen.

Recording of both and eye movements was initiated when the subject was seated in a rotating chair, and discontinued when the chair rotation was stopped.

3. Experimental procedures

Six months prior to conducting the full-scale experiment, we checked the operation and safety of the device during parabolic flight maneuvers. We confirmed that even during parabolic maneuvers, rotation was stable up to 150 degrees/second, and the recording apparatus functioned normally. Two months prior to conducting aircraft experiments, ground tests were performed. On the ground, rotation toward the right at 50, 100 and 150 degrees/second was examined. Aircraft experiments were conducted according to the following procedure: (1) Rotation was started at 1.8 G 10 seconds prior to moving into μ G, with the subject's head bent forward (≥ 40°) 5 seconds after moving into μ G (Fig. 1). (2) Flight tests were conducted 5 times on consecutive days, and a minimum of 10 parabolic maneuvers were conducted on each flight. (3) The subject for the first half of one flight was replaced with a different subject for the last half of the flight; the same subject flew twice. (4) Using right rotation at 100 degrees/second as a base, left rotation at 100 degrees/second was implemented in certain cases. (5)

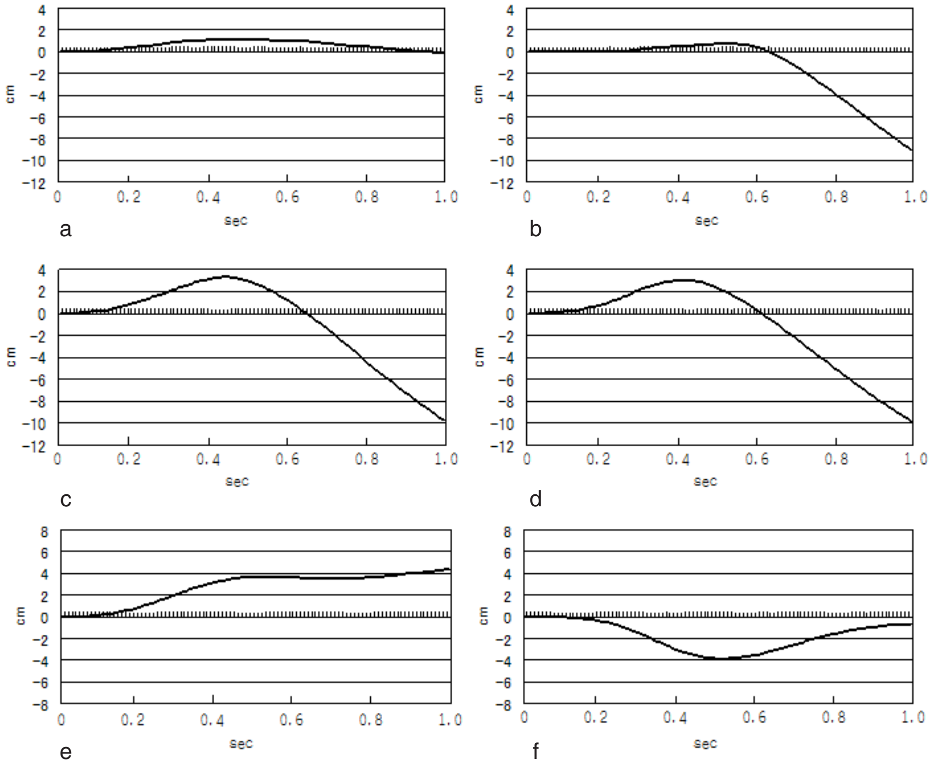

Fig. 2 Linear acceleration records in the same subject were integrated twice, and movement distance (cm) in one second was replicated. Figures indicate stationary values with head bent forward (a), head bent forward during right rotation at 50 degrees/second (b), 100 degrees/second (c), 150 degrees/second (d), right rotation at 100 degrees/second at μ G (e), and left rotation (f). Right movement is indicated as a plus sign and left movement as a minus sign.

The severity of motion sickness was evaluated using the Graybiel score, along with qualitative evaluation of the presence or absence, as well as the strength, of motion sensation.

4. Analysis of results

Body movement:

During right rotation, bending of the head forwards will be perceived by the subject as a force twisting the head in a clockwise direction. As a result, a counterclockwise endolymphatic flow occurs in the subject's semicircular canals, and the center of pressure shifts to the left during upright standing under 1 G conditions. For this reason, we analyzed linear acceleration records in the left-right direction (X), which show the greatest movement, during a 1-second period after forward head tilt. Regarding acceleration before head tilt as zero, we derived peak acceleration values of the upper body in the right and left directions immediately after head tilt. In addition, we derived the speed and distance of motion (cm) at each moment every 10 msec from the g value of acceleration (980 cm/sec^2). Measurements with the least amount of noise were analyzed, and average values were obtained.

Eye movement:

The video tape records were transferred to computer, and modified image analysis software (NIH Image) that is in the public domain was employed for the analysis of eye movement. Eye movements during a 15-second period immediately after forward head tilt were resolved into horizontal, vertical, and rotational components. The peak slow-phase velocities of the rotational and horizontal components and the attenuation patterns of the slow-phase velocity were compared between 1 G and μ G. Records with optimal conditions for each subject were selected for measurement.

RESULTS

1. Body movement records

With the head tilted, the left-right, forward-backward and up-down linear acceleration changes were recorded as thin wavy lines. Recordings were analyzed with the time axis and amplitude of the left-right records amplified. With the head bent forward without rotation at 1 G, no obvious changes in acceleration were recorded. With the head bent forward during right rotation, there was an initial slight acceleration toward the right, followed by conspicuous acceleration to the left [13]. As rotational speed increased from 50 to 100 to 150 degrees/sec, acceleration toward the left increased. Mean acceleration at rotation speeds of 50, 100 and 150 degrees/second for the five subjects was 76.4, 139.1 and 197.4 cm/sec^2, respectively. At μ G, during right rotation, acceleration was initially toward the right, and then changed toward the left. During left rotation, the pattern was reversed. At μ G, the mean accelerations to the right and left at 100 degrees/second were 84.3 and 72.3cm/sec^2, respectively, during right rotation, and 87.2 and 80.8cm/sec^2, respectively, during left rotation. We derived the distance of upper body movement in the left-right direction during a one-second period. At 1 G seated at rest with the head tilted, there was no obvious movement (Fig. 2a). Head tilt during right rotation induced approximately 10 cm of movement toward the left for one second, irrespective of rotation speed from 50 to 150 degrees/sec (Fig. 2b–d). At μ G, during rotation to the right or left at 100 degrees/second, the upper body moved by approximately 4 cm to the right or left, respectively (Fig. 2e, f).

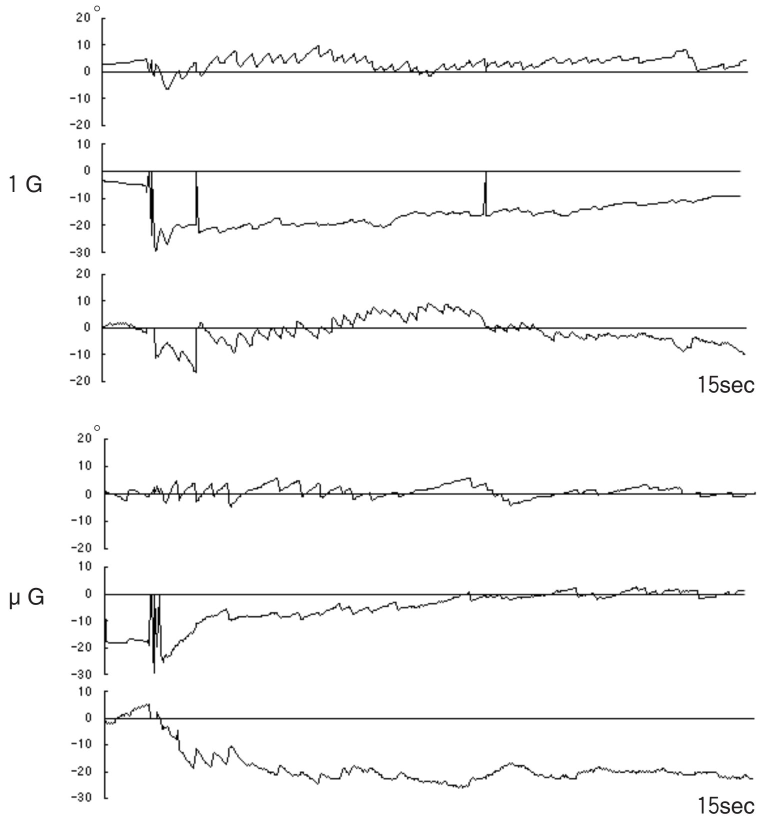

Fig. 3 Analysis results of video tape records for eye movement over a 15-second period immediately after head tilt, under 1 G (upper figure) and μ G (lower figure) conditions. From top to bottom are the horizontal, vertical, and rotational components. The values indicate movement angles, with the plus sign indicating movement to the right for the horizontal, up for the vertical, and the clockwise direction for the rotational component.

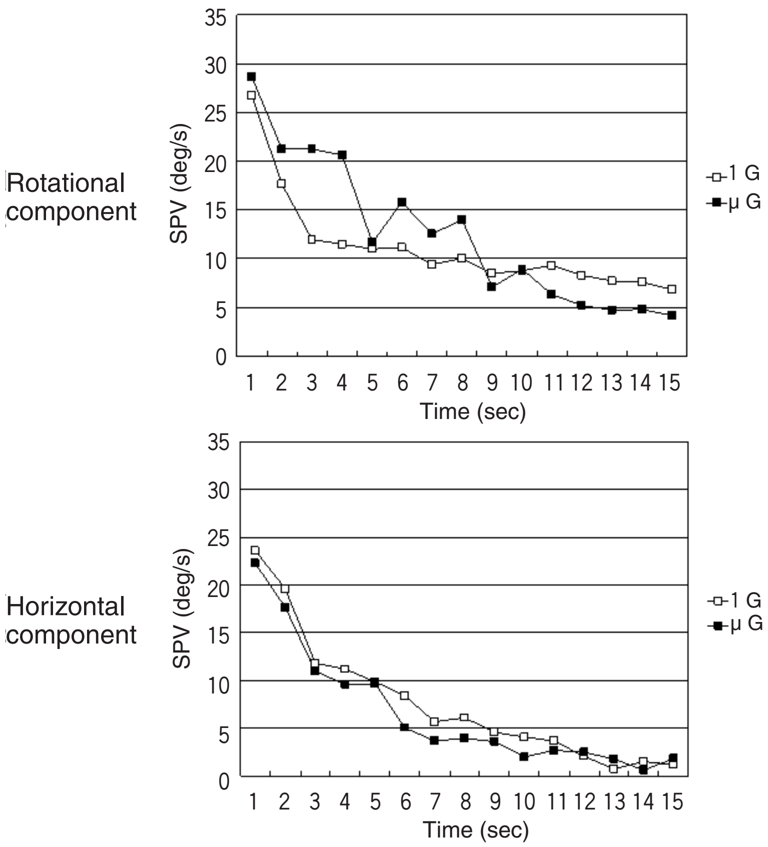

Fig. 4 Mean values of nystagmus slow-phase velocity during a 15-second period after head tilt. Rotational component (upper figure) and horizontal component (lower figure).

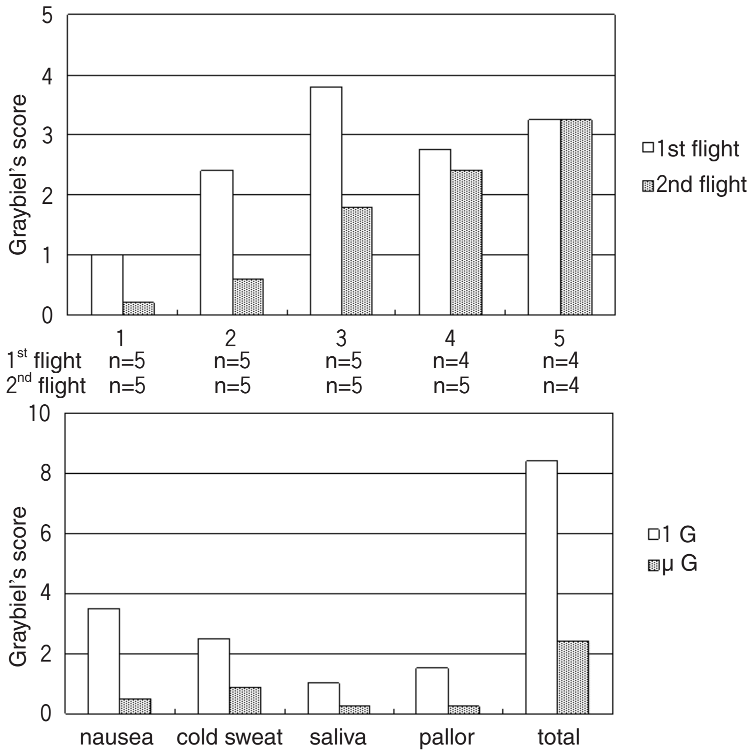

Fig. 5 The upper figure indicates the mean values of Graybiel scores after the completion of each Coriolis stimulation of five trials during the aircraft experiments. N below the figure is the number of subjects. The lower figure indicates the mean value of symptom-specific scores and the sum of scores (Graybiel's score).

2. Eye movement records

Head tilt under either 1 G or μ G conditions caused nystagmus with a strong rotational component lasting for 10 seconds or more (Fig. 3). Since eye movement recordings were irregular immediately after the head tilt, the mean value of the peak slow-phase velocity one second after head tilt, and the time lapse of the mean slow-phase velocity thereafter were compared at 1 G and μ G (Fig. 4). The mean peak slow-phase velocities at 1 G and μ G had rotational components of 26.7 and 28.6 degrees/second, horizontal components of 23.6 and 22.3 degrees/second, and vertical components of 10.2 and 12.1 degrees/second, respectively. Under both 1 G and μ G conditions, the axis of ocular rotation extended from the lower-back to the upper-front part of the head, and the mean peak slow-phase velocities were 35.6 degrees/second at 1 G and 36.3 degrees/second at μ G. There were no obvious differences in the attenuation of the slow-phase velocities between 1 G and μ G conditions.

3. Motion sickness and motion sensation

When Coriolis stimulation was applied at 1 G, all subjects experienced a clear sensation of motion to the left, and strong symptoms of motion sickness. During the aircraft experiment, all subjects experienced the sensation of chair rotation at 1.8 G, but as soon as the plane moved into μ G conditions, the sensation of chair rotation diminished. The sensation of motion during head tilt was far weaker under μ G than at 1 G, and the direction of movement was not uniform among subjects or for repeated measures in the same subject. Symptoms of motion sickness increased with each additional parabolic maneuver (Fig. 5 top). During the first flight, one subject out of the five experienced severe motion sickness, and so the experiment was suspended midway. During the second flight, the experiment was suspended during the fourth parabolic maneuver in this subject. Motion sickness seemed to occur during rotation at 1.8 G before and after head tilt. When the Graybiel scores at the second ante flexion were compared at 1 G and μ G, the score under μ G conditions amounted to only 28.5% of the 1 G value (Fig. 5 bottom).

DISCUSSION

From the 1 G Coriolis stimulation experiments, we reported the hypothesis that posture, eye movement, and movement sensation were determined by the vectorial sum of the visually-perceived external movement and the inertia input from the vestibular apparatus [4]. For the vectorial sum to function as movement information, the system needs an external reference. In this study, we verified the possibility that inertia input would no longer influence vestibular responses under μ G conditions where the external Z axis is lost. In the aircraft experiment, μ G lasts for as little as 20 seconds, and experiments are extremely limited compared with those conducted at 1 G. For this reason, to simplify the experimental conditions, vision was occluded, and experiments were limited to forward head tilt during rotation to the right at 100 degrees/second. To record body movement under μ G, a linear accelerator sensor was employed. From vectorial analysis [14], postural changes during rotation are greatest in the left-right direction when the head is bent forward and backward and in the forward-backward direction when the head is tilted right and left [6]. In this experiment, the measurement accuracy in the left-right direction was influenced by the body's left-right tilt or twist. When the left-right axis is tilted at 1 G, gravitational components are included in the records. Further,

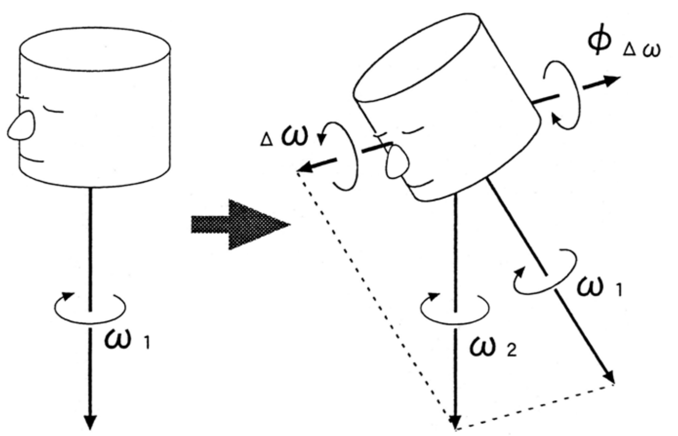

Fig. 6 When the subject bends forward during right rotation, inertia force $\Delta\omega$ is applied at the head, and inertia input $\phi\Delta\omega$ is transferred to the brain from the vestibular apparatus. At 1 G, using external 3D coordinates as a reference that treats gravity as the Z axis, postural change, eye movement and movement sensation faithful to $\phi\Delta\omega$ are output. Under μ G conditions, as external coordinate references disappear, $\phi\Delta\omega$ do not output changes in posture and sensation, but eye movement is induced with the head as reference.

errors may be included during the conversion from linear acceleration to movement distance. Taking these constraints into consideration, we assessed the direction of movement and distance during a one-second period after commencing head tilt. At 1 G, the upper body moved approximately 10 cm toward the left in the direction of inertia input, and at μ G, the upper body moved approximately 4 cm toward the right in the direction of the inertia force. Although peak acceleration at 1 G increased with an increase in the rotation speed, the distance of movement was about 10 cm, irrespective of the speed of rotation. When the head is tilted forward during right rotation, there is initially a clockwise inertia force applied to the head ($\Delta\omega$, Fig 6), immediately followed by a counterclockwise (left) inertia input ($\phi\Delta\omega$, Fig. 6). Since the distance of the upper body movement at 1 G was not changed by the rotational speed at 1 G, body deviation produced by inertial force may lessen the inertia input. Under μ G conditions, the upper body responded to the force of inertia (to the right), but not to the inertia input. Sense of motion and motion sickness severity were also much weaker at μ G than at 1G, as reported [15–17]. Under μ G, because the external Z axis is not input via the otolith organ, the external reference becomes arbitrary. Even if the inertia input is projected, movement information relative to the exterior is not valid (Fig. 6). Since sensation of motion shows a response similar to that of postural changes, it may result from a projection to the higher cortex, where the same reference for postural control applies. Observations and experiments conducted for space and parabolic flight maneuvers reported thus far are consistent in a decrease in the sense of orientation and ataxic control of posture and locomotion [7–12]. Unstable standing and walking after returning to earth indicates a drop in sensitivity to inertia input from the vestibular apparatus [8–12]. Decrease or disappearance of postural and sensation responses clearly indicate that inertia input is being output with external coordinates as a frame of reference. In contrast, from image analysis of video recordings, there were no large differences between 1 G and μ G in nystagmus peak slow-phase velocity immediately after head tilt, or in the subsequent attenuation process. In contrast to the postural reaction, the eyes reacted faithfully toward the inertia input even under μ G. When Coriolis stimulation is applied at 1 G, quite different results are obtained with occluded vision compared with nonoccluded vision, and posture and eye movement show similar responses [6]. Thus, it is inferred that since the inertia input toward the head is valid even under lack of gravity, the ocular response is maintained and has nothing to do with the external reference. When we summarize the results of this experiment as well as previous experiments, we draw the following possibilities: (1) External reference whereby gravity inputs as the Z axis determines posture and eye movement. (2) To represent the external reference, movement of the external world from vision and inertia input from the vestibular apparatus are added together as velocity vectors. (3) External reference is projected to the higher cortex, leading to the sense of motion. (4) External reference is lost within a zero gravity environment, and the sense of motion and postural change responding to the inertia input disappear. (5) Vestibulo-ocular responses are maintained under microgravity because the skull works as a reference to the inertia input. From the present results, we can explain space sickness using the same principle as for motion sickness at 1 G. In space, as inertia input does not produce any sense of motion, the act of moving and the sensation of moving are dissociated, so that when you perform a somersault, you lose your sense of orientation. This situation resembles that seen when walking wearing left-right reversing glasses; as soon as the head is turned to the target direction, the target disappears from the field of vision [1]. When you reside in space for a long period, your body will adapt to conditions that do not use inertia input, and you will of course experience severe imbalance after returning to earth [7, 10, 12]. The hypothesis which we are proposing stands up to the test regardless of whether or not vision is occluded, whether 1 G or μ G conditions are in place, movements are active or passive, or whether the observational target is postural or eye movement.

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