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Dynamic analysis of head movements by means of a three-dimensional position measurement system*

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Abstract. By using a newly devised three-dimensional position measurement system, head movements of a normal subject and a patient with congenital strabismus were studied. This system consists of both infrared light-emitting diodes and position-sensitive diodes, which lead to high accuracy and high-frequency response with a position accuracy within 1 mm and angular accuracy within 1°. The electro-oculograph was used for measuring ocular movements. The power spectra of head and eye movements showed a similar frequency component and a similar frequency response with respect to the signal inputs of head movements, so there is a close correlation between the two movements.

Introduction

Previously reported methods for measuring three-dimensional head movements have been performed by means of a gyroscope, potentiometer, magnetic sensor, and other devices, and have certain limitations.

In the study of abnormal head posture, if the head position can be determined dynamically and without making contact, the quantity of information obtained will increase dramatically compared with conventional means. Furthermore, the data will be more accurate and higher in density. For this purpose, we have developed a new three-dimensional position measurement system using a position-sensing device (PSD) and light-emitting diode (LED). This system has the following advantages [3, 4]:

1. Using infrared light, it is possible to measure position without physical contact, whether in a light or dark room.
2. Parallel and rotatory movements of the head can be determined dynamically and measured three-dimensionally.
3. Strict regulations are not required for the camera setting.
4. It is possible to conduct measurements and process data with high precision and high speed.

This system was used in our study to investigate the head movement characteristics of a normal subject and those of a patient with strabismus, and head-eye coordination was studied during various head movements.

Measurement system

The measuring system is composed of an LED light source, a PSD camera, a control unit, and a computer (Fig. 1). For the light source, a high-luminance infrared LED is used. One LED is mounted on each vertex of an equilateral triangle, with each side 30 cm, on a helmet worn by the subject. The light from this LED is received by two PSD cameras. Each camera contains a silicone semiconductor PSD, and when the infrared light focuses on the PSD, a photocurrent is generated. Since the PSD is a resistance element, the magnitude of the photocurrent is inversely proportional to the distance from the focusing point to the electrodes at four corners. Subsequently the PSD camera converts the photocurrent to a voltage, and delivers an analog output voltage proportional to the x and y coordinates of the light spot. Meanwhile, this camera contains a circuit cancelling the background light so as to take in only the data generated by the illumination of the LED.

The control unit turns the LEDs on and off sequentially through the LED driver, performs A/D conversion of the two-dimensional position information of the LED received by the PSD camera, and feeds the data into the computer. The computer calculates, from the data obtained by the A/D conversion, the shift in the center of gravity of the triangle formed by the LED light sources on the helmet worn by the subject. The magnitude of change of the normal vector is based on displacement of the center of gravity.

The precision of this system was, as determined in measurements taken while rotating ±20° around the x-, y-, and z-axes and moving in parallel 40 mm in each axial direction, within 1 mm in parallel movement and 1° in rotatory movement (M. Takeda, 1985, personal communication).

In order to simplify the procedure for setting up the PSD camera and to minimize the setup error, the camera was set at an arbitrary position. In the procedure to calibrate the measurements, four LEDs are used, and a basic model composed of x-, y-, and z-coordinates of the object is created. This model is imaged by two PSD cameras, and the inclination of the camera is determined. The light from the LEDs mounted on the helmet of the subject is received by two cameras, and the three-dimensional position of each LED is determined (Fig. 2). Changes in head movement are measured, and the displacement of the center of gravity of the triangle formed by the three LEDs on the helmet is calculated as the parallel movement, the change in the rotational angle of the normal vector set up on the center

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* Dedicated to Dr. G.K. von Noorden on the occasion of his 60th birthday

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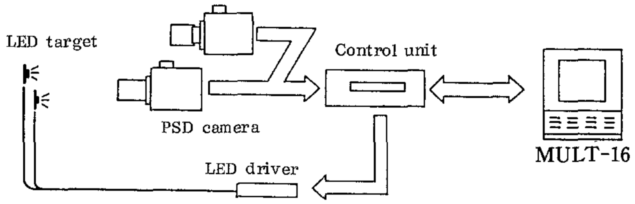

Fig. 1. Three-dimensional head movement measuring system

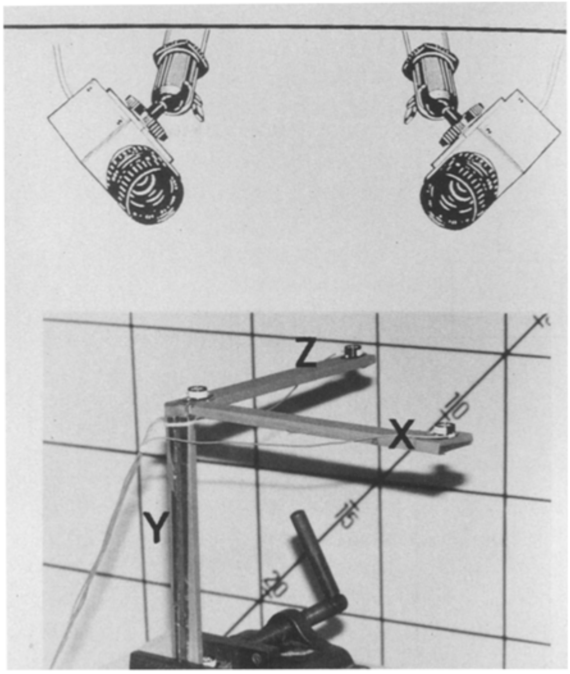

Fig. 2. Three-dimensional head position measurement. Configuration of the basic coordinate axis model and PSD cameras is shown. Model is set so that the z-axis coincides with direction of vision

of gravity as the posture movement. Therefore, the head movement is expressed as a total of six time-series waveforms consisting of the rotatory movements around each coordinated axis and the parallel movement in each axial direction (Figs. 3, 4).

The helmet with the LEDs was mounted on the subject's head while she was seated, and two PSD cameras were set on the ceiling obliquely above the subject. The outputs from the PSD cameras were monitored so that the LEDs on the helmet were within the field of vision of the PSD cameras. Eye movment was recorded at the same time by the electro-oculograph (EOG). Information about the two-dimensional position of the LED light sources obtained by the PSD cameras and the EOG signals were fed into the computer, and the three-dimensional position of each LED and eye movement were calculated. The results of these measurements were studied by time-series waveform, plane projection loci, and frequency analysis.

Subjects and methods

In order to investigate the state of head-eye coordination of a normal subject (28-year-old man) during head motion the following two types of head motion were measured, and the results were analyzed by employing the techniques of time region, frequency region, and space region analysis:

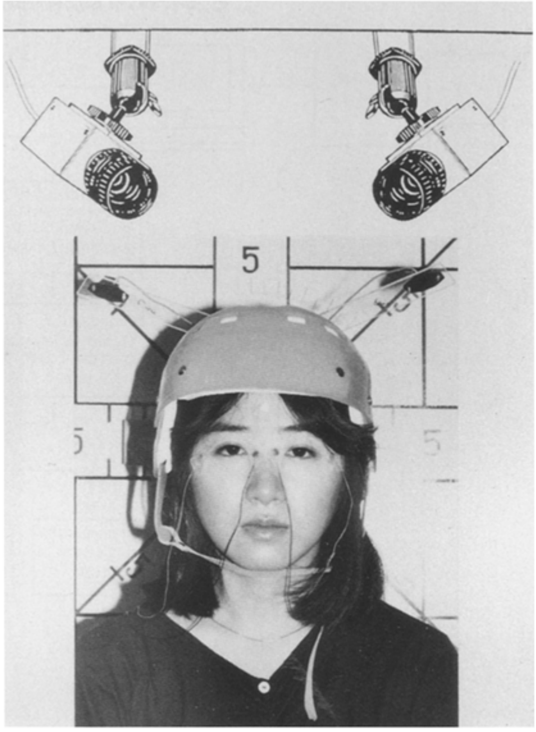

Fig. 3. Method of measuring head motion; configuration of subject and PSD cameras

1. Horizontal saccadic head motion
2. Horizontal sinusoidal head motion

In order to study the head motion characteristics of a patient with strabismus, a patient with congenital strabismus with abnormal head posture (16-year-old girl) and a normal subject (24-year-old woman) were measured similarly during horizontal saccadic head motion and horizontal sinusoidal head motion. The results were compared by the same analytic methods.

Results

Horizontal saccadic head motion

The subject was asked to look alternately at the two fixed points 20° to the left and 20° to the right at a frequency of 0.4 Hz (Fig. 5).

Studying the movement waveform for more than 16 s during the first half of the measurement of a measuring sampling time of 132 ms and 256 measuring points, we noted rectangular waves in the x-, y-, and z-axis components of posture movement, the x-axis component of position movement, and eye movement. As for the posture movement in particular, the so-called interference wave with a 180° phase deviation from the y-axis waveform was observed not only in the y-axis rotation of the principal component of saccadic motion, but also in the x- and z-axis components (Fig. 6).

In the x-axis component of the position movement, and in the x-, y-, and z-axis components of the posture movement, a cyclic motion of 0.43 Hz, similar to the input signal, was observed.

In both eyes, a frequency of 0.43 Hz, similar to the input signal, and frequency components 1.29 Hz and 2.14 Hz of

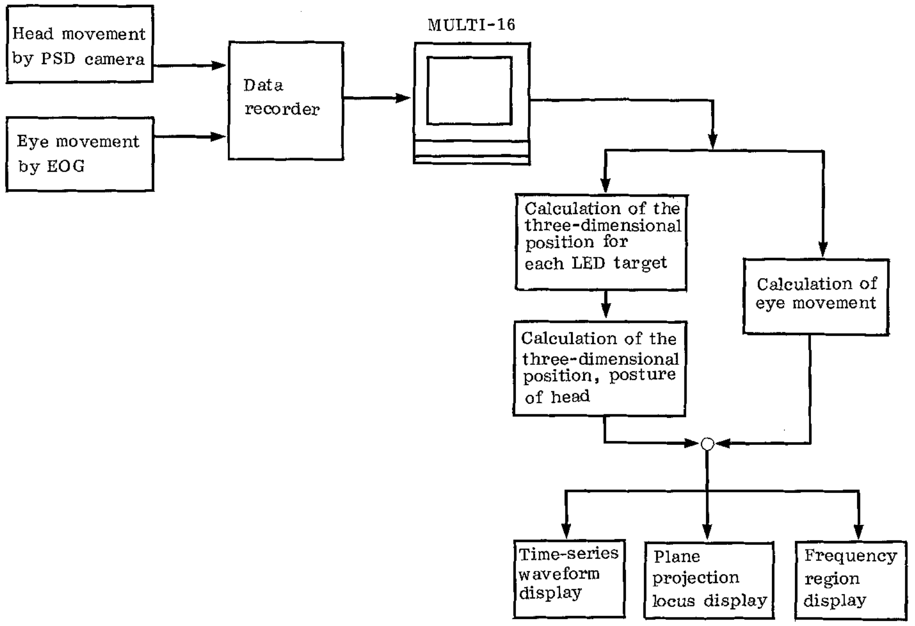

Fig. 4. Measurement processing system

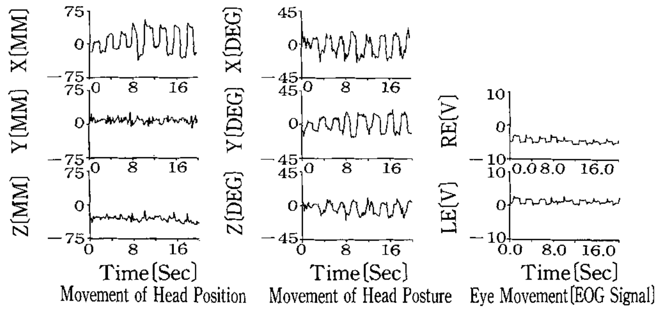

Fig. 5. Time-series waveform of head and eye movement during saccadic head motion by normal subject. Pursuit by head ±20° (0.4 Hz)

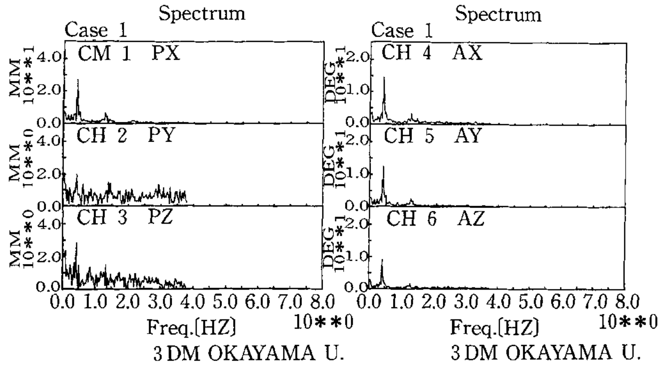

Fig. 6. Spectra of position movement (*left*) and posture movement (*right*) in saccadic head motion in normal subject. Pursuit by head ±20° (0.4 Hz)

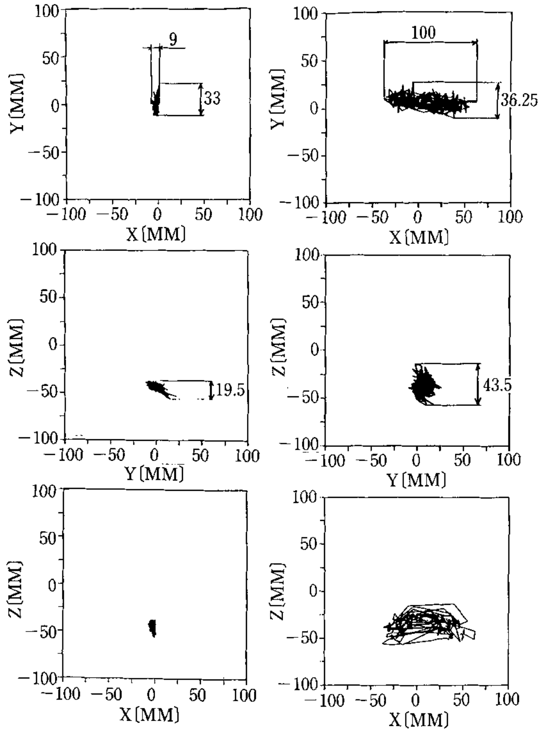

Fig. 7. Plane projection locus of saccadic motion. *Left*, normal subject: pursuit by eye ±20° (0.4 Hz); *right*, patient: pursuit by head ±20° (0.4 Hz)

its odd-number oder were observed. A strong correlation between head and eye movements was noted.

To visualize the three-dimensional analysis of head movement more clearly, head position movement was projected onto two-dimensional planes in the three directions of front (x−y), side (y−z), and elevation (z−y), and the movement loci were drawn (Fig. 7). As a result, during the horizontal saccadic motion of 20° to the right and left, head position movements of 43.5 mm in the longitudinal direction, 36.24 mm in the vertical direction, and 100 mm in the horizontal direction were noted.

Horizontal sinusoidal head motion

The subject was asked to move the head in a sinusoidal fashion at frequencies of 0.375 Hz and 0.75 Hz over a hori-

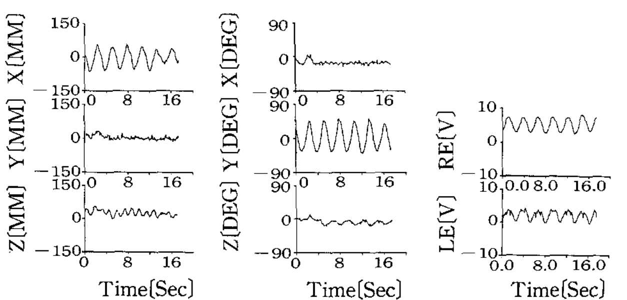

Fig. 8. Time-series waveform of head and eye movements during horizontal sinusoidal swivel by normal subject ±30° (0.375 Hz)

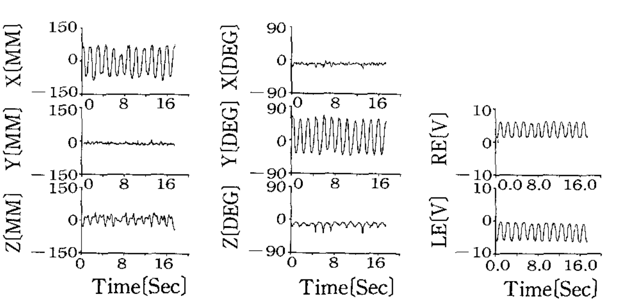

Fig. 10. Time-series waveform of head and eye movement in horizontal sinusoidal head motion by normal subject: horizontal swivel ±30° (0.75 Hz)

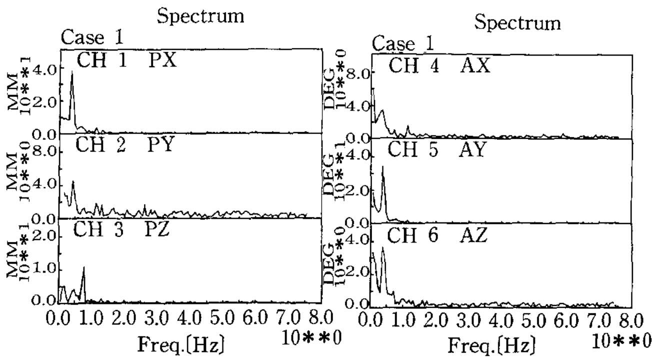

Fig. 9. Spectra of position movement (*left*) and posture movement (*right*) during horizontal sinusoidal head motion by normal subject: horizontal swivel ±30° (0.375 Hz)

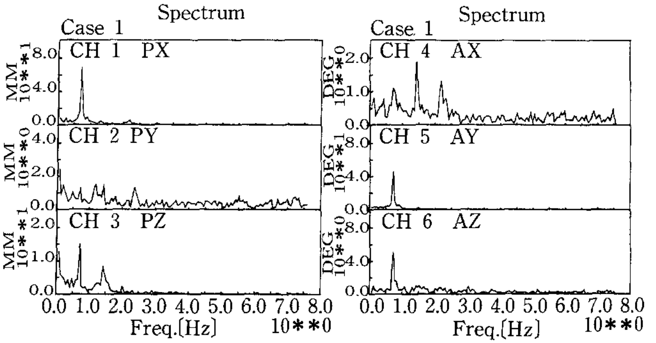

Fig. 11. Spectra of position movement (*left*) and posture movement (*right*) during horizontal sinusoidal head motion by normal subject: horizontal swivel ±30° (0.75 Hz)

zontal range of +30°, while fixating on a target 1 m directly in front of him. The sampling time was 66 ms (Fig. 8).

Sinusoidal waveforms were observed in the y-axis and z-axis components of the posture movement, x-axis and z-axis components of the position movement, and eye movement. In the posture movement especially, sinusoidal waves were noted, not only in the y-axis component of the principal components of the movement; small amplitude waveforms were also noted in the z-axis component which were 180° out of phase, in reverse with those in the y-axis. In the position movement small amplitude, z-axis component waveforms having a frequency double that of the waveform of the x-axis component were observed, and different movement waveforms from those of the saccadic motion were recognized (Fig. 9).

Periodic movements of 0.36 Hz, similar to the input signal, were noted in the x-axis component of parallel movement, and those of 0.18 Hz, 0.47 Hz, and 0.75 Hz in the z-axis component. Of these, the 0.75 Hz component of z-axis parallel movement was twice the input signal, and it was felt that the period of the parallel movement in the z-axis direction was doubled by the y-axis rotation. In the y and z components of the posture movement, a cyclic motion of 0.36 Hz, similar to the input signal, was observed.

In both eyes, cyclic movements components of 0.36 Hz, similar to the input signal, were observed, and a strong correlation between the head and eye movements was suggested (Fig. 10).

Quasisinusoidal waveforms were noted in the y- and z-axis components of posture movement, x- and z-axis components of position movement, and eye movement. Particularly in the posture movement, waveforms were observed not only in the y-axis component of the principal components of movement, but also in the z-axis, where a component of small amplitude, differing in phase by 180° to this waveform, was observed. In the position movement, a waveform of the z-axis component of small amplitude having a period double the waveform of the x-axis component was observed (Fig. 11).

Cyclic movements of 0.71 Hz, similar to the input signal, were observed in the x-axis component of parallel movement, and those of 1.4 Hz in the z-axis component. In the y- and z-axis components of posture motion, cyclic movements of 0.71 Hz, similar to the input signal, were noted.

In both eyes, frequency components approximating the input signal of 0.75 Hz were observed, and a strong correlation between head and eye movements was noted, not only during saccadic motion, but also during sinusoidal motion.

The sinusoidal movements of 0.375 Hz and 0.75 Hz were compared in the plane projection locus, and in both cases longitudinal and vertical movements were detected, but the movement in the horizontal direction of the principal components of motion was very distinct. The 0.75 Hz movement was smaller for the vertical movement, and was greater for the longitudinal. The clearest pattern of movement was horizontal (Fig. 12).

Head movement characteristics of the patient with strabismus

As a result of saccadic motion at a frequency of 0.3 Hz to fix visually on targets placed 20° to the right and left in the horizontal direction, in the normal subject, rectangular waves were observed in the y-axis component of the posture movement, together with a z-axis waveform of

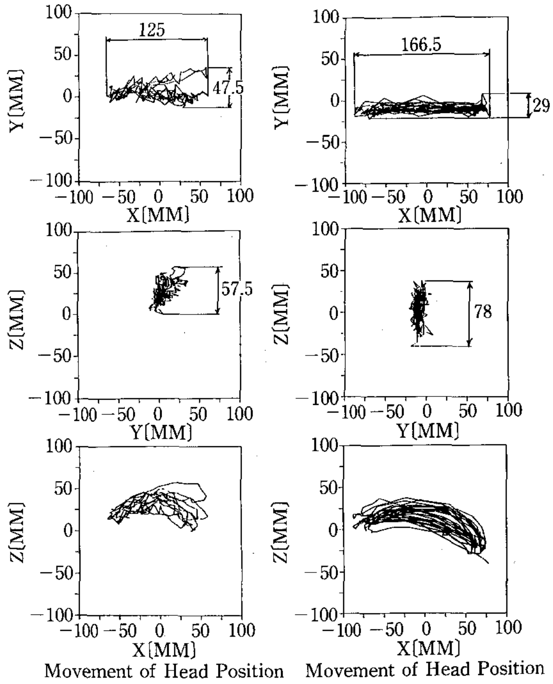

Fig. 12. Plane projection locus of horizontal sinusoidal head motion: plane locus at 0.375 Hz (*left*) and at 0.75 Hz (*right*)

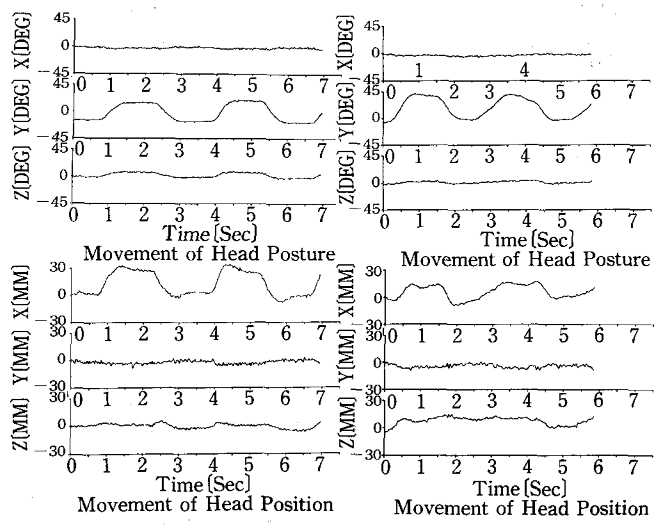

Fig. 13. Time-series waveform of saccadic head motion in a normal subject (*left*) and a patient with strabismus (*right*): posture movement (*top*); position movement (*bottom*). Both subjects: pursuit by head ±20° (0.3 Hz)

about 6°, synchronized with this y-axis component (Fig. 13). In the patient with strabismus, although similar rectangular waveforms were observed in the y-axis component, the profile was not as clear, and no waveform was recognized in the z-axis component. In the parallel movement, a rectangular waveform of the x-axis component was observed in the normal subject, but the waveform of the patient was irregular. There was no clear difference in the z-axis component between the two subjects.

In the normal subject, the horizontal movement pattern of the principal component of motion was clear, while in the patient, the longitudinal movement was definite but the horizontal movement was unclear (Fig. 14).

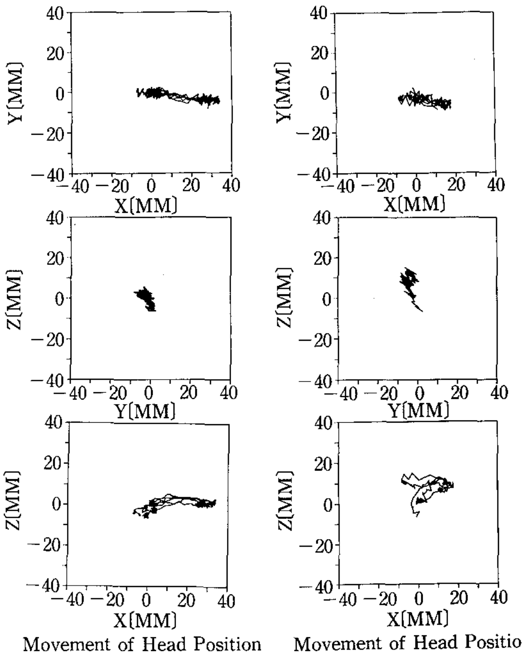

Fig. 14. Plane projection locus of saccadic motion of a normal subject (*left*) and a patient with strabismus (*right*). Both subjects: pursuit by head ±20° (0.3 Hz)

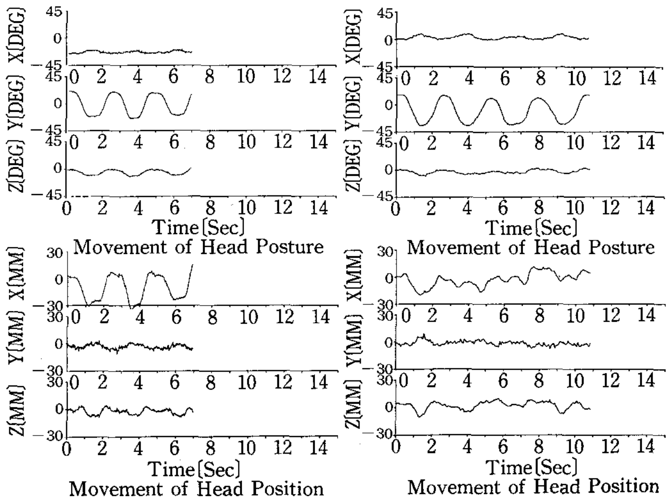

Fig. 15. Time-series waveform of sinusoidal motion of a normal subject (*left*) and a patient with strabismus (*right*), posture movement (*top*), position movement (*bottom*). Both subjects: horizontal swivel ±20° (0.4 Hz)

As a result of the horizontal sinusoidal swivel motion of the head at 0.4 Hz alternating between 20° to the right and left while maintaining a fixed point of focus straight ahead, the posture movement of the normal subject (sampling time 132 ms) included smooth sinusoidal waves in the y-axis component, a waveform of z-axis component which was synchronized with an amplitude of about 15°, and an interference wave of extremely small amplitude in the x-axis component (Fig. 15). In the patient with strabismus (sampling time 26 ms), a smooth sinusoidal waveform was observed in the y-axis component of the posture movement, but the sinusoidal waveforms of the x-axis and y-axis components were smaller in amplitude than in the normal

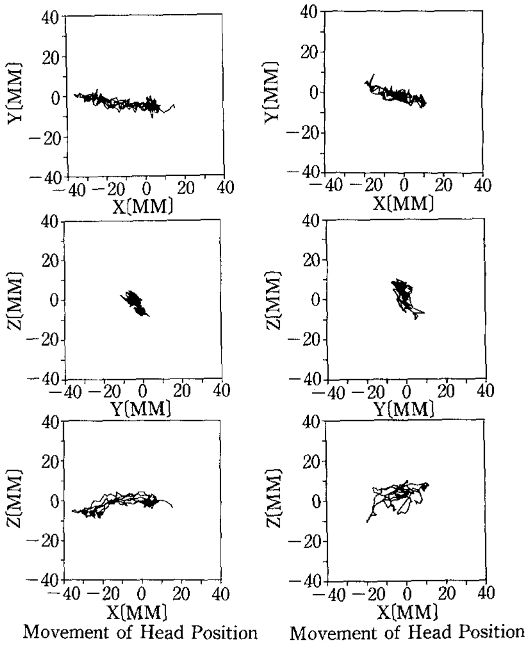

Fig. 16. Plane projection locus of sinusoidal movement of a normal subject (*left*) and a patient with strabismus (*right*). Both subjects: horizontal swivel ±20° (0.4 Hz)

subject, and the waveform of the z-axis component was ill defined.

In the position movement of the normal subject, a waveform like a sinusoidal wave, although not as smooth was observed in the x-axis component. Furthermore, interference waves of small amplitude were noted in the y-axis component, and small waveforms which were synchronized with the x-axis component waveform were observed in the y-axis component. In the patient, a waveform was observed in the x-axis component; however, it was irregular as compared with that of the normal subject. Furthermore, although waveforms were observed in the y-axis component and z-axis component, they were poorly defined and irregular (Fig. 16).

In the normal subject, the horizontal movement pattern by swivel motion was clear, but in the patient, while the longitudinal movement was definite, the horizontal movement was not.

Discussion

Head movement is a synthesis of position and posture movements, and during saccadic motion in particular, postural movement displays waveforms in all axial components even while the subject is moving in one specified direction. This reveals head movement to be the synthesis of multiaxis rotations. Additionally, postural movement during swivel motion in the horizontal direction was composed mainly of rotatory movement in the y-axis component accompanied by movement in the z-axis component, which tell us that even this simple head movement is, like saccadic motion, a synthesis of movement comprised of complicated multiaxis rotations.

In order to examine head and eye coordination in the horizontal direction during head movement, the y-axis components of posture movement during saccadic motion and the eye movements were displayed in 256 measured points and magnified. Large-step waveforms were noted in the eye movement during the initial stage of the head movement. With time, however, the waveforms degenerated, and spike-like waveforms appeared (Fig. 17).

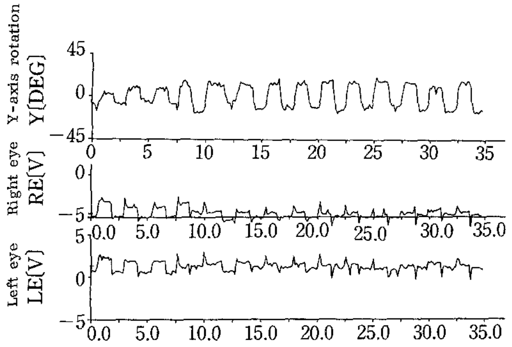

Fig. 17. Relation between head y-axis rotation and eye movement during saccadic head motion

This is felt to occur because the eye moves faster when following quick pulsing motions and the head follows. This generates an EOG signal in the initial stage of the step. Collating the waveforms of the eye movement and head movement, we see that the impulsive movement of the eye precedes the head movement, while, on the other hand, the head was rotating even after the end point of the impulsive movement. From the end of this impulsive movement until the end of the head movement, the eye rotated in a reverse direction of head rotation due to the vestibular oculomotor reflex, which seems responsible for maintaining the stability of the gaze. It has been reported previously that, when catching a peripheral target, eye movement precedes head movement [1]. This was confirmed by our measuring system, but since the sampling time was relatively long, it will be necessary to study shorter intervals in order to elucidate the relation with the impulsive movements of the eye.

The mechanism by which compensatory eye movements occur during swivel motion was observed by the reaction corresponding to 0.375 Hz and 0.75 Hz in the head movement, frequencies we often experience clinically [4], and in both cases, the phase deviation of the head and eye movement waveforms was 180°. Assuming a smooth pursuit system, in which the gain begins to decline at 0.5 Hz, the result of a swivel motion of 0.75 Hz in particular, seems to expand the frequency range in which the gaze is stabilized, as the vestibular oculomotor reflex compensates for both the optokinetic system and smooth pursuit function.

The reason why the patient with strabismus had difficulty is smoothly executing head movement as compared with the normal subject seems to arise from coordination disturbances of the vestibular-visual system of the central nervous system [3], given that this patient's situation was also complicated by abnormal head posture. This coordination forms part of the extrapyramidal system in the brain stem, and if any trouble occurs here, the voluntary motions of the head, neck, and trunk of the body, unconsciously or reflectively adjusted by this system, cannot be executed smoothly, and the tension balance of the muscles is broken. This leads to abnormalities of head movement. However, it is necessary to examine the mechanism of abnormal head posture more closely, and further studies will be necessary.

Conclusions

Using a three-dimensional head-movement measurement system which utilized a camera incorporating high-luminance infrared light-emitting devices and semiconductor position-sensing devices, head movement was measured, and the results were analyzed by time-series, frequency, and space-region techniques.

During saccadic head motion in a normal subject, high-fidelity frequency responses of the head and eye movements to motion stimulation inputs were obtained, and a close coordination between the two was noted. In the initial stage of saccadic motion, eye movement preceded head movement.

During sinusoidal motion in a normal subject, the compensatory action of the eye to the head movement was studied. As a result, frequency components similar to the input signals were noted in both head and eye movements, and a close coordination to the stimulation inputs was observed.

In a patient with strabismus who had normal head posture, the smooth head movements of the normal subject were not observed.

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