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Comparing the accuracy of video-oculography and the scleral search coil system in human eye movement analysis

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Abstract

The measurement of eye movements in three dimensions is an important tool to investigate the human vestibular and oculomotor system. The primary methods for three dimensional eye movement measurement are the scleral search coil system (SSCS) and video-oculography (VOG). In the present study, we compare the accuracy of VOG with that of SSCS using an artificial eye. We then analyzed the Y (pitch) and Z (yaw) component of human eye movements during saccades, smooth pursuit and optokinetic nystagmus, and the X (roll) component of human eye movement during the torsional vestibulo-ocular reflex induced by rotation in normal subjects, using simultaneous VOG and SSCS measures. The coefficients of the linear relationship between the angle of a simulated eyeball and the angle measured by both VOG and SSCS was almost unity with y-intercepts close to zero for torsional (X), vertical (Y) and horizontal (Z) movements, indicating that the in vitro accuracy of VOG was similar to that of SSCS. The average difference between VOG and SSCS was 0.56°, 0.78° and 0.18° for the X, Y and Z components of human eye movements, respectively. Both the in vitro and in vivo comparisons demonstrate that VOG has accuracy comparable to SSCS, and is a reliable method for measurement of three dimensions (3D) human eye movements.

Keywords: Human eye movement; Saccade; Smooth pursuit; Optokinetic nystagmus; Torsional vestibulo-ocular reflex

1. Introduction

The measurement of eye movements in three dimensions (3D) is an important tool to investigate the human vestibular and oculomotor system. The primary methods for measuring 3D eye movements are the scleral search coil system (SSCS) [1,2] and image processing techniques (video-oculography or VOG) [3–11]. A major shortcoming of SSCS is the invasive use of a contact lens embedded with a coil, which limits testing time and has restricted its clinical use [11]. VOG systems, which measure 3D eye position from digitized video data, use three main techniques: tracking of distinct iral landmarks and representing eye position in Fick coordinates [3–6]; polar cross-correlation, where the iral intensity along a circular sampling path is used to determine ocular torsion [7–11], which has been extended to correct for the geometric distortion inherent in projecting the eyeball onto a two-dimensional (2D) image [11]; and a rotation vector analysis method that has been developed by Imai et al. [12]. The last technique reconstructs the 3D position of two points on the eye from the 2D video images, and calculates the rotation vector representing the eye movement in 3D space.

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Two-dimensional (i.e., horizontal and vertical) VOG systems are increasingly used in the laboratory and clinical setting, although the SSCS is still regarded as the ‘gold standard’ for 3D eye movement measurement. Although SSCS has a much higher sampling rate than VOG (typically >500 Hz compared to 60 Hz for VOG) improvements in 3D VOG algorithms have led to systems with accuracy comparable with SSCS. There have been a limited number of direct comparisons between VOG and other existing techniques. Moore et al. [10] have compared a polar cross-correlation VOG system with the 35 mm photographic technique of Markham and Diamond during centrifugation of human subjects, and there was no difference between the results obtained from both systems [10]. Furthermore, in a simultaneous comparison of their VOG system (using polar cross-correlation and geometric correction) and SSCS during centrifugation of a human subject, Moore et al. [11] demonstrated a difference in the torsional (*X*) component of eye movement of only 0.05 ± 0.14° (mean and S.D. over 3 min) between the two techniques. In the present study, we compare the accuracy of our new VOG system [12] with that of SSCS over a comprehensive range of 3D eye movements. We first used an eye movement simulator and examined the relation between the set angle of an artificial eyeball and the angle measured by both VOG and SSCS. We then analyzed human eye movements during saccades, smooth pursuit, optokinetic nystagmus (OKN) and per-rotatory nystagmus (PRN) in normal subjects using our VOG and SSCS.

2. Methods

2.1. The analysis of the movement of simulator eyeball

We developed a simulator of eye movement [12]. The eyeball was made from acrylic resin with a diameter of 3 cm. The eyeball could rotate around three axes, horizontal, vertical and torsional, and had a sensor of rotational angle. We attached a scleral search coil (Daiichi Medical Co. Ltd.) to the eyeball. SSCS was the electromagnetic system for measuring eye movement. The artificial eye was rotated manually around the three axes to angles of -30 to 30° in 5° steps. The movement of the artificial eyeball was simultaneously recorded by a video camera (RealEyes, Micromedical Technologies) onto analogue videotape. The videotape images were converted to digital images by a frame grabber (PCV-R63K, SONY) and analyzed by our own VOG system [12]. We first constructed a 3D frame of reference and determined the space coordinates of the center of eyeball rotation, the center of the pupil, and an iris freckle. From the movements of two points on the eyeball in the 2D image, that is, the center of the pupil and an iris freckle, the 3D rotation of eyeball could be calculated. In this paper, we use rotation vectors to characterize the 3D eye position by a single rotation. The rotation vector is aligned with the axis of the rotation, and its length is proportional to the size of the rotation. Any 3D eye position can be reached by rotating the eye from the reference position about a single axis. The reference position was defined as the position that the

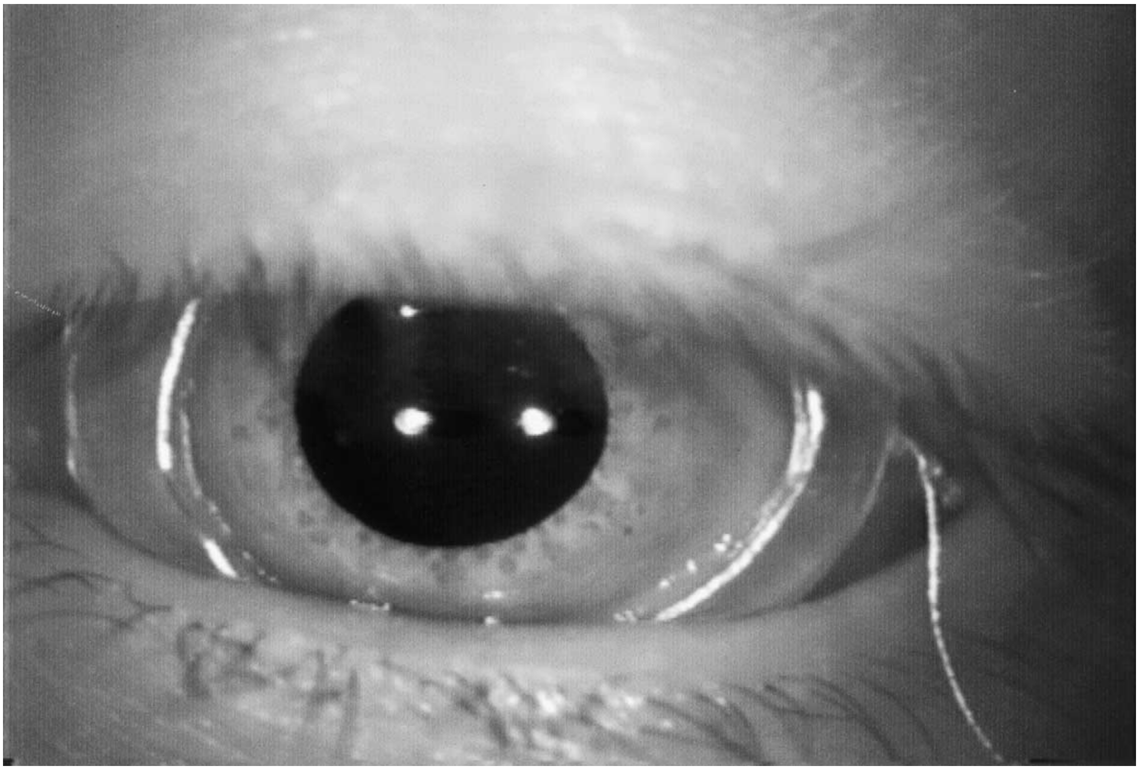

Fig. 1. An image of a subject’s left eye obtained from the VOG camera, showing the scleral search coil.

rotational angle of eyeball was set to 0 for the three axes (i.e., ‘looking’ straight ahead). These coordinates (*X*, *Y*, *Z*) were defined such that *X*-axis was parallel to the naso-occipital axis (positive forward), *Y*-axis parallel to the inter-aural axis (positive left), and *Z*-axis normal to the *X*–*Y* plane (positive upwards). *X*, *Y*, and *Z* components mainly reflect the roll, pitch and yaw component, respectively. The rotation vector $\boldsymbol{r}$ describing a rotation θ about the axis $\boldsymbol{n}$ is given by $\boldsymbol{r} = \tan(\theta/2) \times \boldsymbol{n}$, where $\boldsymbol{n}$ is a unit vector whose direction represents the axis of the eye movement. As Euler angles are more commonly used in the oculomotor field, we have represented the eye position using axis–angle representations [13,14], using Euler angles given as $2 \times \tan^{-1}$ (magnitude of rotation vector).

2.2. *The analysis of real human eye movement in vivo*

Four normal healthy male subjects were used in this study. They were between 23 and 33 years of age (average age 30 years). Informed consent was obtained from all the subjects prior to this experiment. In this study, we used our own VOG system [12] and SSCS simultaneously (Fig. 1). Visual stimulation was given to the subjects to induce saccades, pursuit and optokinetic nystagmus (OKN) (FSK-10, DAIICHI MEDICAL Co. Ltd.). A dot of diameter 1 mm was projected onto a cylindrical screen (diameter, 78 cm), which surrounded the chair, and used to elicit saccadic and smooth pursuit eye movements. The frequency of the dot movement was 0.3, 0.5 and 0.75 Hz, and range of the movement was 10°. A moving light and dark striped pattern was projected onto the same screen, and elicited pure horizontal and vertical OKN. The angular velocity of the striped pattern was 30 and 60°/s. Prior to insertion of the scleral search coil, the subjects’ left eye was anesthetized by oxyprocaine hydrochloride. Subjects wore both a scleral search coil and goggles with a video camera focused on the left eye. The primary position was defined as the position the eye assumes when the subject was looking straight ahead with the head was held upright. In order to induce torsional eye movement, the subjects were rotated manually at frequencies of 0.1, 0.2, and 0.3 Hz with their head tilted 90° backward (facing the ceiling), held in place with a bite-bar (Fig. 2), which elicited torsional per-rotary nystagmus.

3. Results

3.1. *Analysis of the movement of simulated eyeball*

We measured the rotation of the simulator eyeball around the *Z*-axis and compared 3D eye position measured by VOG with those obtained from SSCS (Fig. 3). Because the

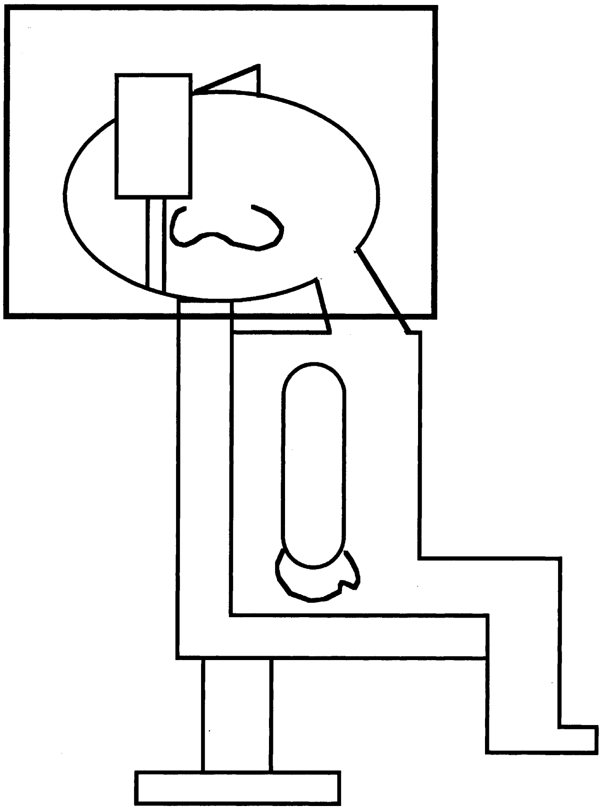

Fig. 2. Subjects were rotated manually with their heads tilted 90° backward (facing the ceiling), held in place with a bite-bar, to induce torsional nystagmus.

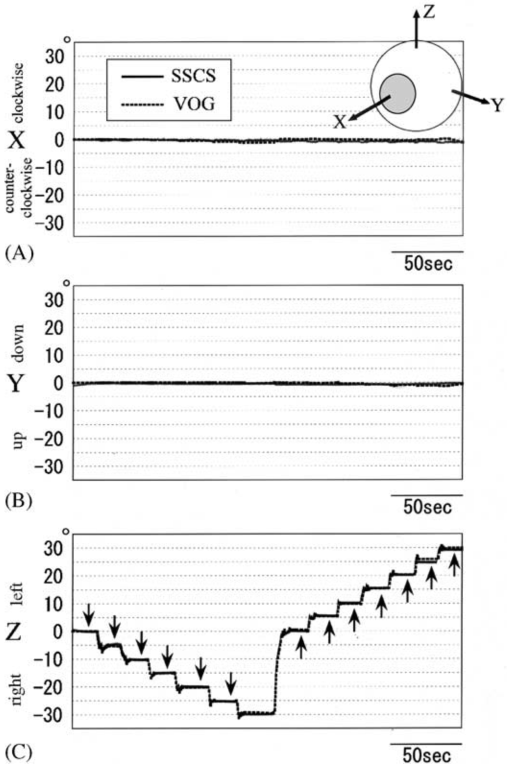

Fig. 3. *X*, *Y*, and *Z* components of movement of the artificial eyeball measured by VOG and SSCS during rotation about the *Z*-axis. (A) *X* (roll) component. (B) *Y* (pitch) component. (C) *Z* (yaw) component. The arrow indicates the point at which the angle of the artificial eyeball was stable. The rotation angles measured by VOG and SSCS were almost identical.

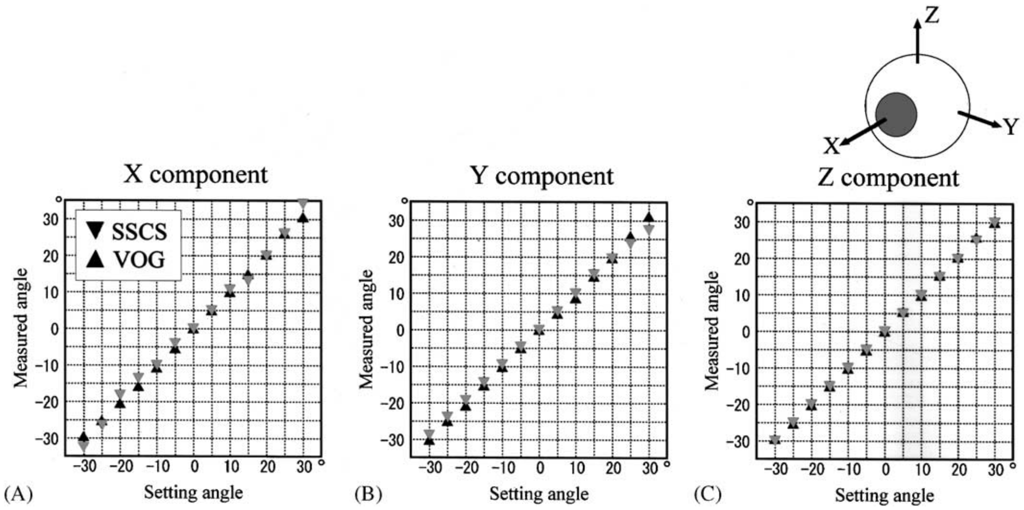

Fig. 4. The relation of each position component between the set angle of the artificial eyeball and the angle measured by VOG and SSCS. (A) *X* (roll) component when the simulator was rotated about the *X*-axis. (B) *Y* (pitch) component when the simulator was rotated about the *Y*-axis. (C) *Z* (yaw) component when the simulator was rotated about the *Z*-axis.

rotation was purely horizontal, no *X* and *Y* components were observed (Fig. 3). In Fig. 4, we show the relation between the set angle and the angle measured by both of VOG and SSCS. There was little difference between the two techniques, which both exhibited a strong linear relationship between the measured and actual angles of the artificial eye about the three axes. Using the VOG system, the mean difference between the set angle of the eyeball and the measured value

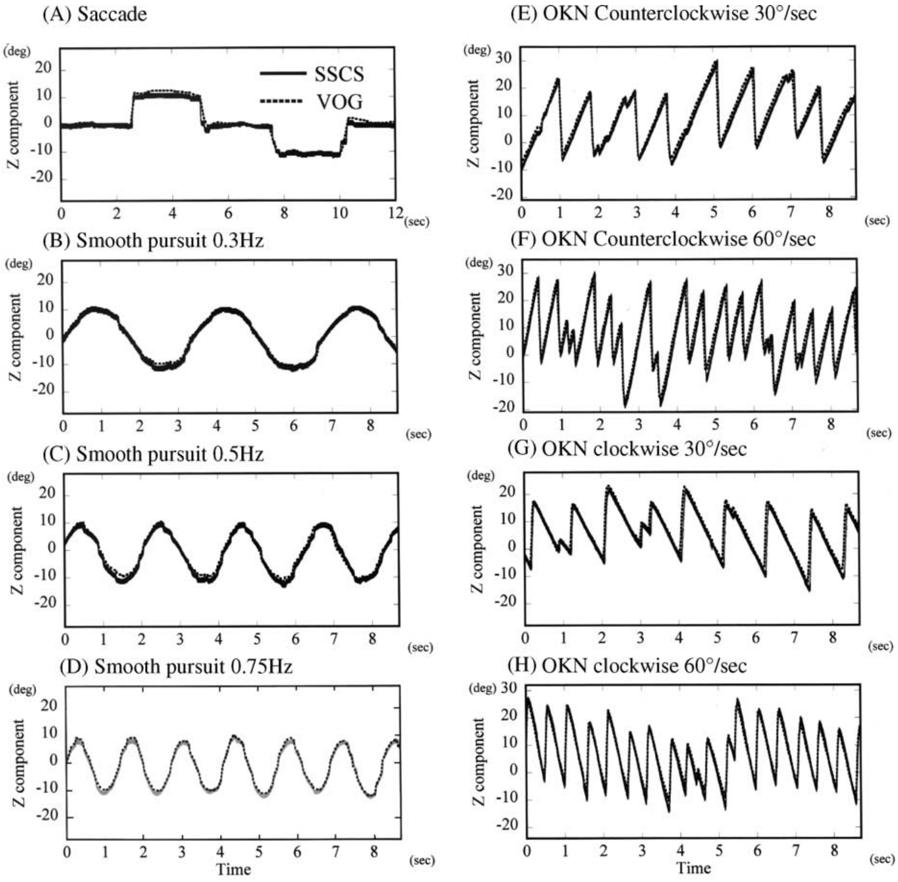

Fig. 5. *Z* (yaw) component of human eye movement measured by VOG and SSCS during (A) horizontal saccadic eye movement, (B) 0.3 Hz horizontal smooth pursuit, (C) 0.5 Hz horizontal smooth pursuit, (D) 0.75 Hz horizontal smooth pursuit, (E) 30°/s counterclockwise OKN, (F) 60°/s counterclockwise OKN, (G) 30°/s clockwise OKN, and (H) 60°/s clockwise OKN.

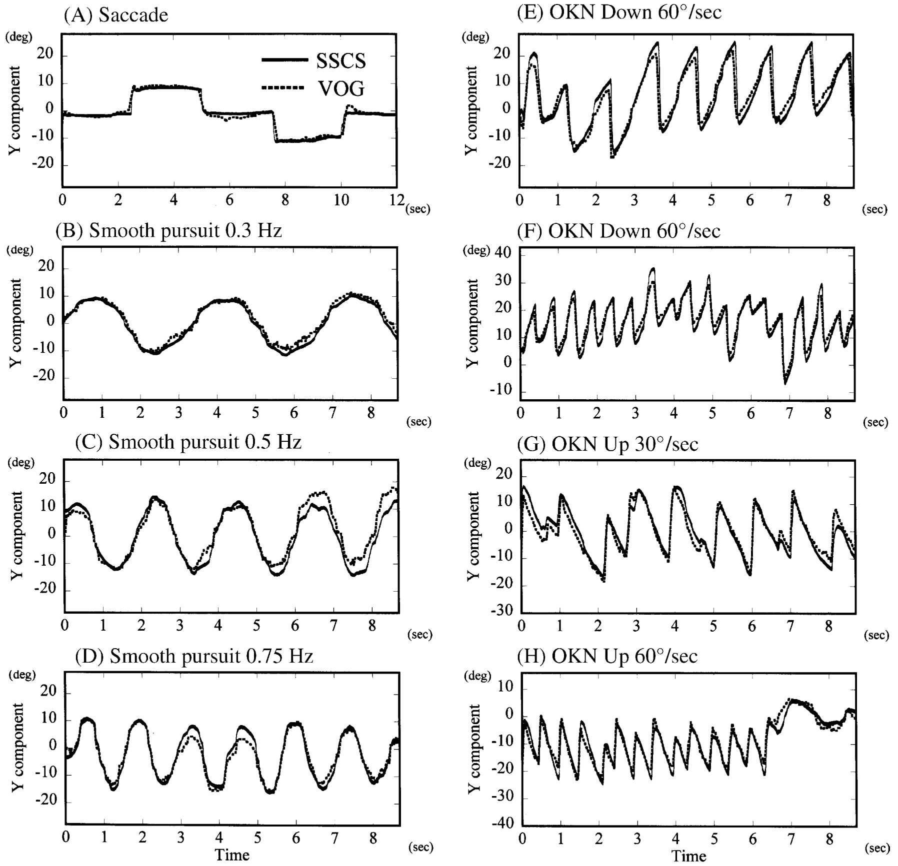

Fig. 6. *Y* (pitch) component of human eye movement measured by VOG and SSCS during (A) vertical saccadic eye movement, (B) 0.3 Hz vertical smooth pursuit, (C) 0.5 Hz vertical smooth pursuit, (D) 0.75 Hz vertical smooth pursuit, (E) 30°/s downward OKN, (F) 60°/s downward OKN, (G) 30°/s upward OKN, and (H) 60°/s upward OKN.

was 0.52°, 0.62°, and 0.36° (maximum values 1.04°, 1.34°, and 0.87°) for rotation about the *X*-, *Y*- and *Z*-axes, respectively. The linear relationship between the angle measured by the VOG system and the actual angle of the artificial eye (x) was represented by the following equations:

$$X_{\mathrm{VOG}} = 1.02x - 0.05 \quad (R^2 = 0.9995)$$

$$Y_{\mathrm{VOG}} = 1.01x - 0.18 \quad (R^2 = 0.9992)$$

$$Z_{\mathrm{VOG}} = 1.01x + 0.07 \quad (R^2 = 0.9997).$$

Similar results were obtained for the SSCS system. The mean difference between the set angle of the eyeball and the measured value was 1.62°, 0.94°, and 0.45° (maximum values 4.21°, 2.55°, and 1.08°) for rotation about the *X*-, *Y*- and *Z*-axes, respectively. The linear relationship between the angle measured by the SSCS system and the actual angle of the artificial eye (x) was as follows:

$$X_{\mathrm{SSCS}} = 1.04x + 0.33 \quad (R^2 = 0.9943)$$

$$Y_{\mathrm{SSCS}} = 0.96x + 0.06 \quad (R^2 = 0.9993)$$

$$Z_{\mathrm{SSCS}} = 0.98x - 0.01 \quad (R^2 = 0.9997).$$

where R is correlation coefficient. The all values of R^2 were almost 1. This means that the relationship between the actual

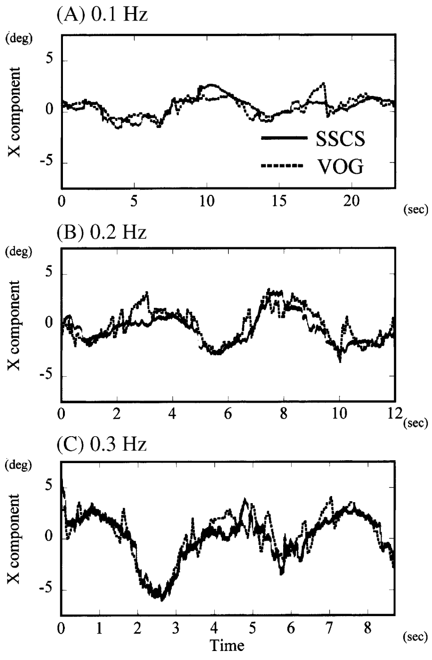

Fig. 7. *X* (roll) component of human eye movement measured by VOG and SSCS during (A) 0.1 Hz torsional per-rotatory nystagmus (PRN), (B) 0.2 Hz PRN, and (C) 0.3 Hz PRN.

angle of the artificial eye and the angle measured by VOG or SSCS system was high.

3.2. Analysis of human eye movement in vivo

We measured the movement of the human eye in vivo and compared 3D eye position measured by VOG with that obtained using SSCS. Horizontal (Z) components of saccadic eye movement, smooth pursuit, and OKN of a subject are shown in Fig. 5, and Z components measured by VOG overlaid those measured by SSCS. The maximum difference of the Z component between VOG and SSCS among all subjects was 1.62°, with an average difference of 0.18°. The Y components of vertical saccadic eye movement, smooth pursuit, and OKN of a subject are shown in Fig. 6. The maximum and mean difference of Y components measured by VOG and SSCS were 6.34° and 0.78°, respectively. The torsional (X) component of a subject's torsional PRN is shown in Fig. 7. The X component measured by VOG and SSCS were in close agreement, with a maximum difference of 3.04° and an average of 0.56°.

4. Discussion

The scleral search coil system measures 3D eye position from the voltages induced in coils embedded in an annular contact lens and worn by the subject. Although this system is accurate it is invasive, requiring the use of a topical anaethetic prior to insertion of the annular contact lens, and unsuited for clinical testing [11]. Furthermore, the lens can only be worn for a limited time (40 min), and has a tendency to slip, particularly in roll [11]. Recent advances in image processing have allowed the development of 3D video-based systems for eye movement monitoring. In order to accurately analyze 3D eye position from 2D video images, it is important to take into account the 3D structure of the eye, and only a small number of systems have implemented this approach [11,12]. In this paper, we examined the accordance between the 3D eye movement data measured by our VOG system [12] and SSCS.

Using an artificial eyeball, a close linear relationship was found between the set angle of the eyeball and both the VOG and SSCS systems, over a range of -30° to 30° rotations about the X-, Y- and Z-axes. Similarly, in vivo comparison of VOG and SSCS measurements of human saccadic, smooth pursuit and OKN eye movements and torsional nystagmus in normal subjects were in close accordance. This confirms a previous study, which found a mean difference of 0.05° between torsional (X) VOG measures and SSCS [11]. Although data using an artificial eyeball were a close linear relationship, there is still difference between the angle measured by VOG system and SSCS system. This is the reason why the difference in X component between VOG system and SSCS system in vivo was caused. The average difference of Z component in the present study was three times larger than previous report [10]. When we investigated the accuracy of Z component in vivo, we used almost pure horizontal eye movement. During pure horizontal eye movement, the value of Z component analyzed by polar cross-correlation is calculated using only horizontal movement in two dimensional eye images. The error is caused only by the analyzed value of horizontal movement in two dimensions. But when we analyze eye movement in three dimensions, we used not only the value of horizontal movement in two dimensions but also the information of the depth of eyeball. If there is some error when we calculate the depth of eyeball, the error affects the value of Z component. These might be the reason why the average difference of Z components in the present study was three times larger than previous report. These two systems use widely differing methodologies, with VOG using image processing and the present 'gold standard' SSCS utilizing magnetic fields to induce coil voltages. The fact that the eye position measurements obtained from both systems were almost identical demonstrates the viability of VOG for 3D eye movement measurement. Thus, 3D VOG is a feasible alternative to scleral search coils for clinical recording of 3D eye movements in humans.

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