AN OBJECTIVE AND AUTOMATED METHOD TO MEASURE EYE ALIGNMENT

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ABSTRACT

A novel method to measure the manifest and latent angles of eye misalignment (ETBT) is presented. The method is based on a stereo-camera remote eye-gaze tracking system that estimates the position of the center of curvature of the cornea and the direction of the optical axis of the eye without subject calibration. The performance of ETBT was compared with the gold standard clinical test (APCT) in 12 adult subjects. The comparison between ETBT and APCT demonstrated a good agreement of 0.54±2.75Δ for horizontal angles and −0.5±2.52Δ for vertical angles. The repeatability of ETBT was within 0.67±2.74Δ for horizontal angles and −0.44±2.19Δ for vertical angles, which is slightly better than the reported repeatability of APCT. Since ETBT requires limited subject cooperation, it might be suitable for infants and young children.

INTRODUCTION

One of the most common clinical conditions that require early therapeutic intervention in young children is ocular misalignment (strabismus). In many cases, strabismus is treated by surgery. Successful surgical planning is dependent on accurate estimation of the maximum (latent) angle of misalignment between the two eyes.

With cooperative subjects, the maximum angle of deviation can be accurately measured with the alternating prism and cover test (APCT), during which a subject is required to maintain a stable fixation on a target, while a prism is being held in front of one eye and a cover is switched from eye to eye. APCT cannot be reliably administered, however, in children younger than two years of age due to their short attention span and lack of cooperation.

In uncooperative subjects, the corneal reflex tests (e.g., the Hirschberg Test [1] or the Krimsky Test [2]) are the primary clinical methods to measure the angle of ocular misalignment prior to surgery. These tests measure the manifest deviation only, by comparing the displacement of the virtual image of a light source (corneal reflex that is created by the front surface of the cornea) from the center of the entrance pupil in the fixating eye (with which subject fixates on the light source) and the deviating eye. The accuracy of these tests is very limited [3] due to the clinician's inability to estimate precisely the displacement of the corneal reflex and the inherent variability, among subjects, of parameters (Hirschberg Ratio (HR) and angle kappa [4, 5]) that are required for the translation of the measured displacement, in millimeters, to eye misalignment, in degrees.

Several techniques that use remote eye-gaze trackers were proposed to automatically measure the angle of eye misalignments [6-8]. The methods described in [6, 7] are not suitable for infants and young children, since they require stable head position and accurate fixation on specific targets. The method described in [8] replicates the standard clinical Hirschberg test. It allows for accurate measurements of the displacement of the corneal reflex from the pupil centre but, similar to the Hirschberg test, its accuracy is limited by the inherent inter-subject variability of the HR and the asymmetry of angle kappa between the left and right eyes.

In a recent paper [4] we described a method that was inspired by the Hirschberg test, which tolerates some head movements, does not require continuous fixation on specific targets and use estimates of the personal HR and angle kappa for each subject to calculate accurately the manifest angle of eye misalignment. This method was tested with 5 orthotropic (straight eyes) infants, and theoretical calculations were provided for the expected error in the estimation of the angle of eye misalignment in infants with strabismus [4].

In this paper, we present a novel Eye-Tracker Based Test (ETBT), which allows free head movements, does not require continuous fixation on specific targets and can be used to measure both manifest and latent deviations. The accuracy of the ETBT is evaluated by comparing the maximum (latent) angle of deviation measured by the ETBT and the clinical gold-standard test (APCT) in patients with strabismus. Since the APCT cannot be reliably performed with infants and young children, the comparison is done with cooperative adult patients with strabismus.
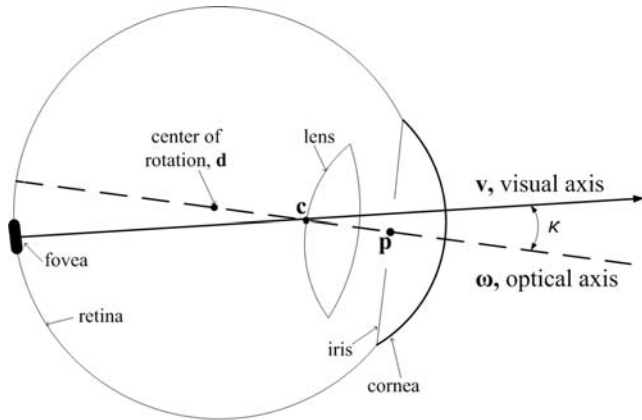
THE METHOD TO MEASURE EYE ALIGNMENT

Figure 1: Simplified schematics of the eye-ball.

In our analysis, we use the eye model that is shown in Figure 1. In the model, the *optical* axis, $\boldsymbol{\omega}$ (the axis of symmetry of the eye) passes through the center of curvature of the cornea, $\mathbf{c}$, and the center of the pupil, $\mathbf{p}$. The *visual* axis of the eye (the line-of-sight), $\mathbf{v}$,

connects the fovea (the region of the highest visual acuity on the retina) with $\mathbf{c}$.

As was shown in [9], using a stereo-camera remote eye-gaze tracking system, it is possible to estimate $\mathbf{c}$ and $\boldsymbol{\omega}$ without any subject calibration procedure. Furthermore, the angle between $\boldsymbol{\omega}$ and $\mathbf{v}$ (angle kappa, κ) in each eye can be estimated using an automated procedure that we described in [4] and was shown to work reliably with infants. When $\mathbf{c}$, $\boldsymbol{\omega}$ and κ are known, the visual axis can be easily estimated.

The point-of-gaze, $\mathbf{g}$, is given by the intersection of the visual axis with the scene. If the eyes are misaligned, the point-of-gaze of the right eye, $\mathbf{g}^R$, will not coincide with the point-of-gaze of the left eye, $\mathbf{g}^L$ (see Figure 2). In such a case, the angle of misalignment is equal to the amount of rotation around the center of rotation of the deviating eye, $\mathbf{d}$, which is needed so that $\mathbf{g}^R$ and $\mathbf{g}^L$ will coincide.
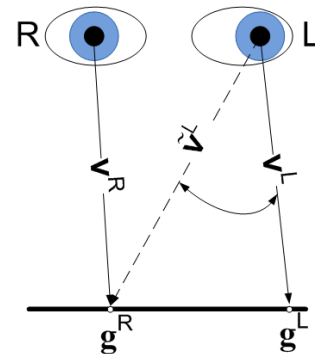

Figure 2: Illustration of eye misalignment: the visual axes of the right and left eye intersect with the scene at two different points.

Without loss of generality, let's assume that the left eye is the deviating eye. In such a case, a unit vector in the direction of its visual axis after the rotation that aligns $\mathbf{g}^L$ with $\mathbf{g}^R$ is given by:

$$\tilde{\mathbf{v}}^L = \frac{\mathbf{g}^R - \tilde{\mathbf{c}}^L}{\left\| \mathbf{g}^R - \tilde{\mathbf{c}}^L \right\|} \qquad (1)$$

where $\tilde{\mathbf{c}}^L$ is a new position of $\mathbf{c}^L$ after the rotation.

Since the change in the location of $\mathbf{c}^L$ due to rotation is relatively small

$(\left\| \tilde{\mathbf{c}}^{\mathrm{L}} - \mathbf{c}^{\mathrm{L}} \right\| \ll \left\| \mathbf{g}^{\mathrm{R}} - \mathbf{c}^{\mathrm{L}} \right\|)$, the following approximation can be made:

$$\tilde{\mathbf{v}}^{\mathrm{L}} \cong \frac{\mathbf{g}^{\mathrm{R}} - \mathbf{c}^{\mathrm{L}}}{\left\| \mathbf{g}^{\mathrm{R}} - \mathbf{c}^{\mathrm{L}} \right\|} \tag{2}$$

Finally, the magnitude of the angle between $\tilde{\mathbf{v}}^{\mathrm{L}}$ and $\mathbf{v}^{\mathrm{L}}$ is given by:

$$\chi = \arccos\left(\tilde{\mathbf{v}}^{\mathrm{L}} \cdot \mathbf{v}^{\mathrm{L}} \right) \tag{3}$$

One should note that χ is the total angle of misalignment with an arbitrary orientation in 3D. Clinically, however, the horizontal and vertical components of the angle of misalignment are measured separately and the total angle has limited value. Therefore, χ should be expressed by its horizontal, χ^{H}, and vertical, χ^{V}, components.

Let's θ be a pan (horizontal) angle, and φ be a tilt (vertical) angle, then the a vector in 3D can be described as:

$$\mathbf{v} = \begin{bmatrix} \sin(\theta)\cos(\varphi) \\ \sin(\varphi) \\ \cos(\theta)\cos(\varphi) \end{bmatrix} \tag{4}$$

Therefore,

$$\theta^{\mathrm{L}} = \arctan(\mathbf{v}_1^{\mathrm{L}} / \mathbf{v}_3^{\mathrm{L}})$$
$$\varphi^{\mathrm{L}} = \arcsin(\mathbf{v}_2^{\mathrm{L}}) \tag{5}$$

where $\mathbf{v}_n$ refers to the n-th component of a vector $\mathbf{v}$.

Similarly,

$$\tilde{\theta}^{\mathrm{L}} = \arctan(\tilde{\mathbf{v}}_1^{\mathrm{L}} / \tilde{\mathbf{v}}_3^{\mathrm{L}})$$
$$\tilde{\varphi}^{\mathrm{L}} = \arcsin(\tilde{\mathbf{v}}_2^{\mathrm{L}}). \tag{6}$$

Finally, the horizontal and vertical components of the angle of eye misalignment are given by:

$$\chi^{\mathrm{H}} = \tilde{\theta}^{\mathrm{L}} - \theta^{\mathrm{L}}$$
$$\chi^{\mathrm{V}} = \tilde{\varphi}^{\mathrm{L}} - \varphi^{\mathrm{L}}. \tag{7}$$

To elicit the maximum (latent) angle of deviation, the eyes should be dissociated by covering one of the eyes. If an infrared filter that blocks visual spectrum but is transparent to the optical system of the eye-tracker is used, the eye under the cover can still be tracked and the method described above can be used to measure the maximum angle of deviation.

EXPERIMENTS

The performance of the ETBT was studied with 12 adult subjects that were recruited from the Toronto Western Hospital (TWH) orthoptists' clinic. The study conformed to the tenants of the declaration of Helsinki and was approved by the research ethics board at the TWH. Four of the 12 patients had esotropia, 4 had exotropia, 2 had IV-th nerve palsy, one had VI-th nerve palsy and one patient had Dissociated Vertical Deviation (DVD).

First, the participants were examined by an experienced orthoptist and the maximum angle of deviation for a distant fixation (6 m) at a primary (straight ahead) gaze direction was measured with the APCT. The range of angles of eye misalignment was from −27.5Δ to 30Δ (prism diopters) horizontally, and from −5Δ to 10Δ vertically.

Next, the maximum angle of deviation was measures with ETBT. During the experiments, participants sat approximately 65 cm from the eye-tracking system (VISION 2020-RB, El-MAR Inc., Toronto, Ontario, Canada) that estimated the coordinates of the pupil-centers and corneal reflexes of the two eyes. The center of the curvature of the cornea and the direction of the optical axis of each eye were estimated as described in [9]. The angle kappa in each eye was measured when the patient fixated momentarily on a target on a computer monitor at a distance of 6 meters while the fellow eye was covered. Finally, the maximum angle of deviation was estimated using the method described in the previous Section.

To reduce the noise in the measurement of eye-misalignment, 30 estimates of χ^{H} and χ^{V} were averaged to obtain the final estimate of eye-misalignment. To achieve dissociation between the two eyes, an infrared transparent occluder was used to cover one of the eyes. The entire ETBT procedure was repeated twice (with few minutes of rest between tests) to assess the repeatability of the ETBT [10].

The average difference (±Standard Deviation, SD) between the measurements with the APCT and the ETBT was 0.54±2.75Δ for horizontal angles and −0.5±2.52Δ for vertical angles.

The average difference (±SD) between two independent measurements by the ETBT was 0.67±2.74Δ for horizontal angles and −0.44±2.19Δ for vertical angles.

CONCLUSIONS

A novel method to measure the angle of eye misalignment was presented. The experiments demonstrated a good agreement (0.54±2.75Δ for horizontal angles and −0.5±2.52Δ for vertical angles) between the measurements obtained by ETBT and the gold standard (APCT).

Based on the results of a study reported in [11], the standard deviation of the difference between independent measurements by different orthoptists was ±3.03Δ for horizontal angles and ±2.48Δ for vertical angles. This variability can be partially attributed to the accuracy of the measurements by a human examiner, and partially to the physiological variability of the angle being measured. Given that in this study, the agreement between APCT and ETBT is similar to the repeatability of the ETBT and is slightly better than the repeatability between human examiners reported in [11], we can conclude that in adults ETBT has similar accuracy and repeatability as the gold standard (APCT). Also, since measurements of eye-misalignment by two different techniques exhibit very similar variability, one can argue that physiological variability might be the most significant contributor to the overall variability.

In previous studies [4, 5] we have introduced a method, an Automated Hirschberg Test (AHT), that enables objective measurements of manifest deviation in infants. The ETBT described in this paper can be used to measure both manifest and latent angles of deviation. ETBT requires even less subject cooperation than the AHT and is less sensitive to head movements and therefore should be the preferred method to measure eye-misalignment in infants. Our next step is to evaluate the ability of the ETBT to measure the maximal angle of deviation in infants and young children. Based on the results with adults, the ETBT might provide a more complete, repeatable and accurate measurement of eye misalignment in infants than current clinical techniques.

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