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Measurement of Torsional Eye Movement Using Terminal Points of Conjunctival Blood Vessels

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Abstract

The angle of torsional eye movement has small amplitude, a high degree of resolution and precision will be required. In the current mainstream method of obtaining the angle of torsional eye movement using an iris pattern, it has been difficult to ensure measurement with a tolerance of 1.0(degree) or less at all times due to changes in the deformation of the iris pattern. We wish to propose a method for high-speed and high-precision measurement of the torsional eye movement by the conjunctival vessel extraction method where attention is paid to the conjunctival vessel end located on the outer edge of the iris as a site impervious to changes in the diameter of the pupil. In the step of evaluation, the vessel end position is measured by visual observation based on the image of torsional eye movement captured from three persons, and the tolerance of this system is calculated. It has been possible to take measurements with a precision of 0.24(degree) or less at a processing speed of 30(fps) or more, even when there is a change in the diameter of the pupil.

1 General Instructions

In the field of study using the method of measuring torsional eye movement is employed, sickness from excessive image viewing is evaluated by the analysis of the characteristics of the torsional eye movement with respect to the visual stimulus, and LASIK of eye cornea surgery using measurement of torsional eye movement to control the laser of cutting the cornea. However, the torsional eye movement occurs only within the range of amplitude of about 12(degrees). Thus, Applications using measurement of torsional eye movement require a high degree of resolution and precision. Further, since processing is preferably performed at a real-time processing speed, the processing speed is required to be 30 fps or more. However, Measurement with a tolerance of 1.0(degree) or less is difficult according to conventional method. This is because the iris pattern is deformed when the size of the pupil changes. Although there are the methods being studied to solve this problem[1][2], it is difficult to take measurement with a tolerance of 1.0(degree) or less when there is a greater change in the pupil diameter.

Thus, we propose the method of measuring the torsional eye movement by tracking the "terminal points of conjunctival blood vessels" illustrated in Fig. 1, which were not in the conventional method. Since the terminal points of conjunctival blood vessels are not subjected to the deformation due to the reaction of the pupil, the torsional eye movement can be measured with high precision. It should be noted, however, that not all the terminal points of conjunctival blood vessels can be employed. Only the terminal points of conjunctival blood vessels connected to the cornea can be used (Fig. 2).

Further, In our conventional method[3], That method used only one point of a conjunctival blood vessel which manually selected by user. However, there are two or more terminal points of conjunctival blood vessels. To ensure correct measurement of the rotational eye movement, automatic selection of the terminal point not blocked by the noise of an eyelash or others must be made at every measurement. The above-mentioned problems can be solved by our proposed method, where the position of the targeted terminal points of conjunctival blood vessels are obtained by identifying the contour of the iris, and a terminal point not blocked by noise is automatically selected by using the similarity in pattern matching.

To evaluate our proposed method, the true value of torsional angle for eye movement using eye images of three persons is obtained, and this value is compared with the torsional angle estimated by this system so that the precision of our method will be obtained, and the adequacy of our method will be justified.

1.1 Test environment

A small-sized monochromatic CMOS camera (FireFlyMV by PointGrey Inc.) is attached to the head using a goggle as illustrated. Similarly in this case, two types of illuminations fixed on the spectacles are used to highlight the pupil iris pattern and conjunctival vessel. The infrared LED is applied to inclease the contrast of the pupil and the iris, and the blue LED

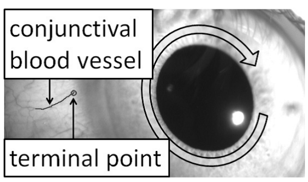


Figure 1. Relation of conjunctival vessel end position and torsional eye movement.

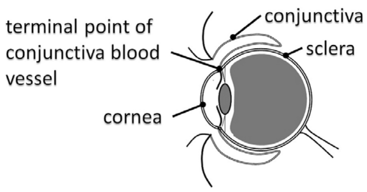


Figure 2. Terminal point of conjunctiva focused in this study.

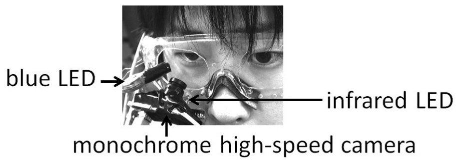


Figure 3. Experimental device.

is applied to increase to the contrast of conjunctival blood vessel. This blue LED emits visible light. If this light is applied to the retina, the subject will be adversely affected. To avoid this, the light should be applied only to the area around the conjunctival blood vessel within the scope of irradiation.

2 Proposed method

The following describes the processing flow of extracting the terminal points of conjunctival blood vessels obtaining the angle of eye rotation. The flow in the proposed method includes: 1) Setting of basic coordinates. 2) Detection of terminal point of conjunctival blood vessel as preprocessing. 3) Definition of region for template matching using the conventional method [2]. 4) Template matching of the terminal point of conjunctival vessel

2.1 Setting of basic coordinates

To calculate the direction of torsional eye movement and angle of eye rotation, an elliptical coordinate system along the contour of the pupil is obtained. The pupil area is characterized by fewer pixels. This characteristic is utilized to obtain the area of lower pixel by a process of binarization, thereby extracting the pupil area. The contour of the pupil area having been obtained is subjected to ellipse approximation by means of the method of least square, and an coordinate system (Fig. 4) is set up where the center of the approximated ellipse is assumed as the center of the pupil, and the major axis of an ellipse passing through the center of the pupil has a 0°. In this coordinate system, the elliptical center coordinates can be represented by the parameters, h as the coordinate in the direction of the major axis, w as the coordinate in the direction of the minor axis, ϕ as the angle in the counterclockwise with respect to the major axis, and θ as the inclination of the ellipse with respect to the camera coordinate system, where the coordinates (x_0, y_0) of the image captured by the camera is assumed as the origin. The formula for converting desired elliptical parameters (w, h, θ) into desired elliptical camera coordinates (x, y) can be defined as follows:

$$\begin{cases} x = x_0 + w \cdot cos(\phi)cos(\theta) + h \cdot sin(\phi)sin(\theta) \\ y = y_0 + w \cdot sin(\phi)cos(\theta) + h \cdot cos(\phi)sin(\theta) \\ w = \frac{a}{b}h \end{cases} \quad (1)$$

2.2 Detection of terminal point of conjunctival blood vessel as preprocessing

The following describes the technique of automatically detecting the terminal point of the conjunctival blood vessel to be tracked as preprocessing: Since the terminal point of the conjunctival blood vessel used for measurement is located on the contour of the iris, the iris area is obtained to detect the terminal point of the conjunctival blood vessel on the iris side extending from the contour of the iris.

To enhance the contrast between the white of eye and iris, the contour of the pupil is obtained by turning off the infrared LED once. To get the contour of the pupil, record the parameters of the ellipse of the pupil obtained one frame before the infrared LED is turned off, and sample the pixel values along the arrow mark of Fig. 5 from the center of the pupil. Calculate the minimum and maximum values of the pixel values. The mean value between the minimum and maximum values is assumed as the threshold value. Refer to the pixel values from the pupil side. The coordinate greater than the threshold value is recorded as the white/black boundary position on the sampling line. From the elliptical parameters and the coordinates of the white/black boundary position having been obtained, calculate the locus of the ellipse for determining the scope for detecting the terminal points of conjunctival blood vessels.To get the locus of the ellipse, the x, y coordinate values of the white/black boundary coordinates having been obtained, pupil elliptical center x_0, y_0, the length of the major axis a, the length of the minor axis b, and inclination of the

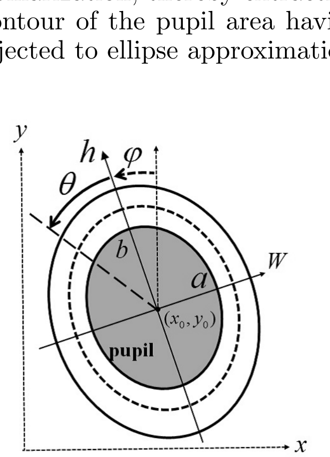


Figure 4. Polar coordinate system obtained with ellipce approximation parameters.

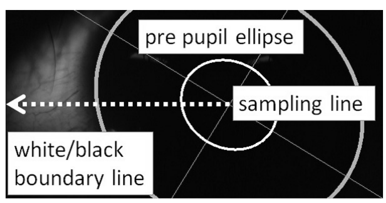


Figure 5. Sampling direction to detect white/black boundary orbit

(a) (b) (c)

Figure 6. Image processing to obtain area of conjunctival blood vessel.(a) Original image,(b) Binarized image,(c) Thinning and noise removal image

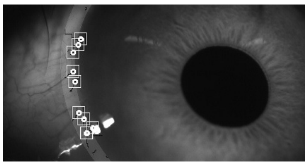


Figure 7. Detected terminal points of conjunctiva blood vessels and region of template image

pupil ellipse ϕ are substituted into the formula (1). The ellipse coordinates (w, h, θ) of the white/black boundary coordinates are obtained by solving this Formula. When the ellipse coordinate θ having been obtained is converted into the camera coordinate (x, y), it is possible to get the locus of the ellipse passing through the white/black boundary coordinates. From this locus of the ellipse, the terminal point of conjunctival blood vessel is detected with respect to the area having a width of 40 pixels or less.

The terminal point of conjunctival blood vessel is detected as follows: The conjunctival blood vessel has a pixel value lower than that of the white of eye constituting the background. Thus, if the pixel value of the original image and subtraction of the original image having been subjected to smoothing process within the scope of 19 pixels are taken, it is possible to get an image where the value in the vessel area is increased but the value of the white of eye as the background is reduced to a constant value. Further, smoothing is performed within the scope of 3 pixels, and "salt and pepper" noise is removed. This image is subjected to binarization using the threshold value, whereby the vessel area can be extracted (Fig. 6b). The Hilditch's thinning algorithm is applied to this image (Fig. 6c). The position closest to the center of the pupil is determined for each of the thin lines having been obtained. These position are assumed as terminal points of conjunctival blood vessels. Then the scope of 20x 20(pixels) centering on each terminal points of conjunctival blood vessels obtained for each thin line (Fig. 7) is recorded as the template image of the terminal point of the conjunctival vessel.

2.3 Definition of region for template matching using the conventional method

The approximate position of the terminal point of the conjunctival blood vessel is found out using the "tentative" angle of torsional eye movement θ_{iris} can be obtain using conventional method[2] and the elliptical parameter on the contour of the pupil. The movement caused by movement of the line of sight can be obtained from the parameter of pupil ellipse. Formula (1) is used to get the parameter of the ellipse that passes through the terminal point at the time of preprocessing and is similar to the ellipse of the pupil. Let us consider how the ellipse for the terminal point is changed when the line of sight is moved. For the center point and inclination of the ellipse, the center of the pupil ellipse x_{0input}, y_{0input} and ϕ_{input} at the time of movement of the line of sight is used. Because of the short distance from the camera, it is possible to ignore changes in the major axis length h_{input} of the ellipse for the terminal point after movement of the line of sight. Thus, the h_{input} is assumed as the same as the major axis length h_{input} of the ellipse for terminal point at the time of preprocessing. The minor axis length w_{input} can be expressed by the following Formula, using the parameters for pupil ellipse a_{input}, b_{input}, and the ellipse parameter h_{temp} passing through the terminal point at the time of preprocessing.

$$w_{input} = \frac{a_{input}}{b_{input}} h_{temp} \tag{2}$$

The movement caused by the torsional eye movement can be obtained from the ellipse for terminal point of the conjunctival blood vessel:

$$\theta_{input} = \theta_{temp} + \theta_{iris} \tag{3}$$

Thus, the approximate coordinates x, y can be calculated by substituting the above-mentioned parameters $x_{0input}, y_{0input}, h_{input}, w_{input}, \phi_{\mathrm{input}}, \theta_{input}$ into the formula (1). The obtained position is assumed as the reference point (Fig. 8).

2.4 Template matching

Template matching is performed between the template of the terminal point of the conjunctival blood vessel obtained at preprocessing and the image of 40 by 40 pixels around the reference point (hereinafter referred to as "input image"). In the process prior to template matching, the template image and input image are processed in such a way that the maximum of the pixel values will be 255, and the minimum of the pixel values will be 0. Thus, the contrast of the vessel end is enhanced. Then template matching is performed using the image where the contrast has been enhanced. The similarity by template matching is calculated by the ZNCC (Zero-mean Normalized Cross-Correlation). Template matching is applied to for all

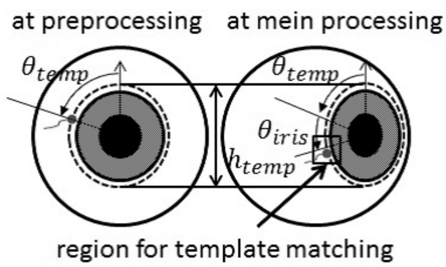
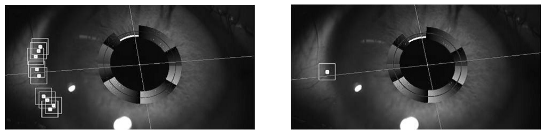


Figure 8. Calculation method to limit region for template matching using elliptical parameters of terminal position at preprocessing, length of pupil major and miner axis, and "tentative" torsional angle obtained by iris-based method[2].

the terminal points (Fig. 9a) using the ZNCC so that the terminal point having the highest similarity is detected. The position where the similarity is maximized is recorded as the site of the terminal point(Fig. 9b). This is converted into the angle θ_{out} using the formula (1). The θ_{out} is subtracted from the angle θ_{temp} at the time of acquiring the template of the terminal point of conjunctival blood vessel having the maximum similarity. This result is the angle of eye rotation using automatic selection of the terminal point not blocked by the noise of an eyelash or others must be made at every measurement.



(a) (b)

Figure 9. Processing of template matching.(a)Template matching is performed between template image and input image (corresponding to template image). (b)Automatically selected terminal point using maximum value of ZNCC.

3 Evaluation test

To evaluate the adequacy of this technique, three subjects were asked to take part in the following test: The average and standard deviation of torsional angle error were measured when both a change in pupil diameter (1) and rotational eye movement (2) were observed. The subjects experienced dark adaptation for about five minutes so that the pupils were enlarged. Capturing of the dynamic image was initiated with the start of measurement. In approximately two seconds, white LED light was applied to the pupils of the subject so that pupils contract. The average tolerance and standard deviation was found between the true value of angle of eye rotation and measurements outputted by the system by visual observation, using 200 dynamic images having been captured. To measure the true value, the template image for the terminal point of conjunctival blood vessel specified by the first dynamic image was displayed on each of the images after the first image and images were compared so that the misalignment between the template image and input image were checked by visual observation. The template image was moved until there is no more misalignment. The center position of the template image was extracted as the information on the position of the terminal point of conjunctival blood vessel. This was converted from the ellipse parameter of the input image to the torsional angle of eye rotation, using the formula (1). The result was used as the true value (Fig. 10). The PC used for the test was the Intel ®core i5, 3.30 (GHz) having a memory capacity of 8GB. Further, the image resolution was 640 x 480 (pixel), and the number of the vessel ends detected was five. The resolution in the measurement of the torsional angle of eye rotation in this case depends on the length from the pupil center to the terminal point of conjunctival blood vessel. It is approximately 0.25 (degree). It has been demonstrated, as a result, that measurement of the rotational eye movement with an average error of 0.24 (degree) or less is possible even when there was a change in the diameter of the pupil (Fig. 10). The value was close to the resolution. As compared with the conventional method using iris-based method[2], this method is characterized in that the precision is independent of changes in the pupil diameter. For the processing speed, The overall processing speed was 30.07 (msec). (33.2 fps).

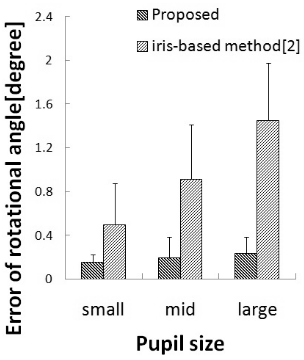


Figure 10. average error of torsional angle and standard deviation when pupil diameter changes

4 Conclusion

This study proposes a method for measuring the torsional eye movement using the terminal position of conjunctival blood vessel. The positional information on the terminal point was obtained by image processing at preprocessing, by defining the terminal positions using template matching, so that the angle of eye rotation was calculated. In the step of evaluation, the torsional eye movement was measured when there was a change in the pupil diameter. As a result, when the critical resolution of the torsional angle of eye movement was about 0.25 (degree), it was possible to measure the torsional eye movement with the average error of 0.24 (degree) or less at a processing speed of 30 times or more per second, even if there is a change in the pupil diameter.

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