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Research Article

Development of a system to detect eye misalignment by using an Arm Cooperative Manipulators HMD equipped with eye-tracking capability

Kayoko Takatsuka, Yoki Nagatomo, Noriyuki Uchida, Takuya Ikeda, Masayuki Mukunoki, Naonobu Okazaki
Faculty of Engineering, University of Miyazaki, 1-1 Gakuen Kibanadai-nishi, Miyazaki-City, Miyazaki, Japan

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ABSTRACT

This study aimed to reduce the effect of the examining environment on accuracy by using an eye movement detection system, a VR head-mounted display. We reproduced the inspection environment in a virtual reality environment and performed the cover test, a basic inspection technique for tropia and phoria. We then developed a system that uses eye data collected by eye tracking to detect the directions and magnitudes of eye misalignment. The Maddox method, an existing testing procedure, was used to verify the accuracy. We have confirmed its effectiveness in detecting the directions and magnitudes of horizontal eye misalignment.

1. Introduction

Eye misalignment, represented by tropia or phoria, is a sign of abnormal vision [1]. This condition is prevalent in almost 3% of the population and may require treatment, although it is not rare. Cranial nerve abnormalities may be the reason when the eye muscles are not aberrant, and symptoms like strabismus may appear as a symptom of severe disorders such as cerebral infarction, thyroid eye disease, myasthenia gravis, or viral infections. Microcirculatory disorders and intracranial diseases, such as cerebral infarction and cerebral aneurysms, pose significant health risks for older adults. Younger individuals may also be susceptible to conditions like multiple sclerosis, highlighting the importance of early detection.

The cover test, a fundamental examination for tropia and phoria, requires an adequate examination room because the distance between the target and the examinee is five meters. The Maddox rod test is another test to check eye position. However, because this is a subjective test, the accuracy of the findings might vary depending on the examiner's expertise and the cognitive abilities of the examinee.

As described above, the examination is time-consuming and dependent on the judgment and skill of the examiner, and some clinical sites find it difficult to perform. In addition to the short supply of qualified examiners (ophthalmologists and optometrists), even the crucial primary screening of 3-year-olds, conducted during a critical time of rapid visual development, is not considered a primary examination and relies on self-reported questionnaire surveys [2].

Currently, most visual function tests, including those for eye position, are not automated [3], [4]. Very few examples of automation exist [5], but they apply only to exotropia. This is because, with other eye position abnormalities, it is difficult to determine the eye position and specify the deviation amount. We believe it is theoretically possible to automate the diagnosis of eye position abnormalities other than exotropia, as the eye movement is significant enough to indicate such issues.

Corresponding author's E-mail: takatuka@cs.miyazaki-u.ac.jp

Therefore, we aimed to develop a system to realize a simple and space-saving eye position testing device that measures pupil positions and instantly calculate and quantify the amount of ocular deviation from the measured values. In our previous study, we automated the cover tests [4] and [6] by controlling the LCD shutter of the 3D glasses with an Arduino microcontroller board. Through the analysis of moving eye images captured on a web camera installed on the 3D glasses, we constructed a system to calculate eye deviation from eye position deviation [7], [8], [9], [10]. This method, however, was susceptible to outside influences, such as the reflection of fluorescent light, affecting its accuracy.

2. Research purpose

In response to the environmental dependency issue above, we utilized a virtual reality head-mounted display (HMD) to create a virtual inspection environment for developing a system for detecting eye position anomalies in an environment independent of the inspection environment [11]. We recreated the inspection environment in virtual reality, executed cover tests in this setting, and developed a system that uses eye data collected by eye tracking to detect the direction and magnitude of eye position anomalies. We validated its accuracy by comparing the results to those gathered with the Maddox method, a conventional testing technique. This system will provide an inexpensive and uncomplicated means to evaluate the state of eye position once completed, and preliminary results might promote medical tests, which will be critical in terms of early diagnosis.

3. Existing methods

3.1 *Cover-Test*

The Cover Test (see Fig.1) requires the examinee to fixate on a target five meters distant or a near target 30 cm away. The examinee has normal alignment if the uncovered eye does not shift for fixation; if it moves inward, the examinee has exotropia; and if it moves outward, the examinee has esotropia, as shown in Fig.1. Two test methods exist: ACT (Alternate Cover Test) and CUT (Cover-Uncover Test). The ACT covers both eyes alternately, making it easy to determine the total amount of deviation. The CUT method covers and exposes an eye, making it easy to observe the amount of tropia and phoria separately.

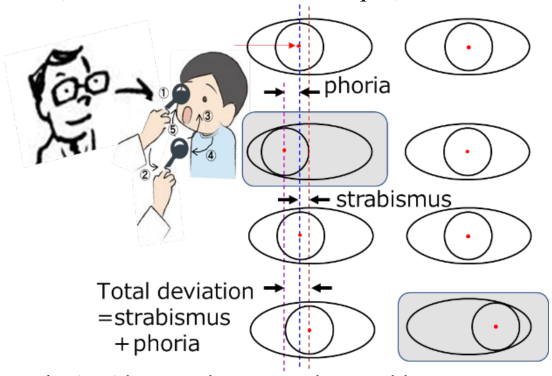

Fig.1 Abnormal amount detected by cover test

3.2 *Maddox inspection*

The Maddox test [12] measures subjective total deviation in cases of binocular disparity, such as phoria, micro-strabismus with peripheral fusion, and intermittent strabismus. We instruct the examinee to look at a point light source five meters away with one eye open and a Maddox rod placed on the contralateral eye as in Fig. 2-(1). If no binocular disparity exists, the point light source superimposes on the red ray as in Fig. 2-(2). Fig. 2-(3) shows that they will not coincide in cases of ocular deviation such as tropia or phoria. If there is no overlap, we place the prism bar in front of the eye wearing the eyepiece, adjust the prism power, and move the prism until the point light source superimposes on the red ray. The prism power at the overlap point is the actual eye deviation. The Maddox rod is placed vertically for examining the esotropia and horizontally for the exotropia to evaluate the amount of ocular deviation.

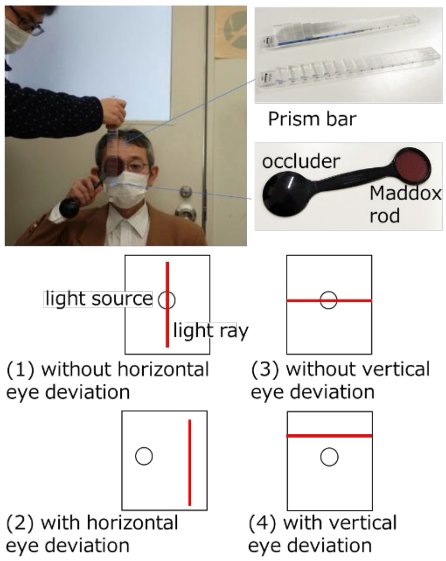

Fig.2 Inspection with the Maddox rod

4. Proposal method

4.1 System Configuration

Fig.3 shows the configuration of this system, which consists of four parts, and makes it possible to perform the same tests as the existing eye position testing method, the cover test 8),9),10).

(1) The HMD "VIVE Pro Eye" [13] worn by the examinee (Fig.3-A).

(2) A link box to exchange data between the HMD and the PC (Fig.3-B).

(3) A PC for building the examination environment, recording eye data, and checking the output status of the HMD (Fig.3-C).

(4) A base station for tracking and analyzing the HMD in a virtual examination room (Fig.3-C).

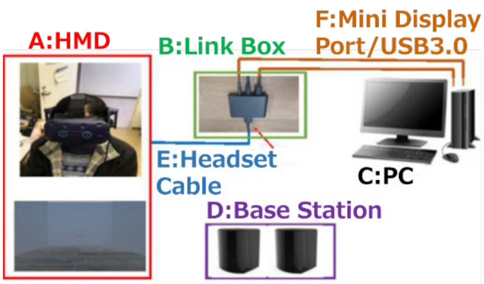

Fig.3 Configuration of the system

4.2 Acquisition of ocular data during Cover-Test (schematic)

We instruct the examinee to maintain fixation on a target, a circle, presented on a screen in the virtual exam room through the VR goggles. ACT operates as follows:

1. In Fig.4-(1), the screen displays an identical target at the same position for both eyes. Pupil center positions are measured and recorded.
2. In Fig.4-(2), a black screen covers only the right eye. Two to three seconds after the gaze position has settled, the pupil center positions are measured and recorded.
3. The black screen is removed from the right eye and then covers the left eye in Fig.4-(3). Measurements and recordings are as above.

4.3 Determination of eye position abnormality based on the data (concept)

From the measurement results obtained using the 4.2 methods, we can conclude that:

・Based on the measurement results in 1 and 2, we suspect the right eye has horizontal phoria if the shift distance of its pupil center position is not zero pre and post covering. We suspect the left eye has horizontal tropia if the shift distance its pupil center position pre and post covering the right eye is not zero.

・Based on the measurement results in 1 and 3, we suspect the left eye has horizontal phoria if the shift distance of its pupil center position pre and post-covering is not zero, and the right eye horizontal tropia if the shift distance from its pupil center position pre and post-covering is not zero.

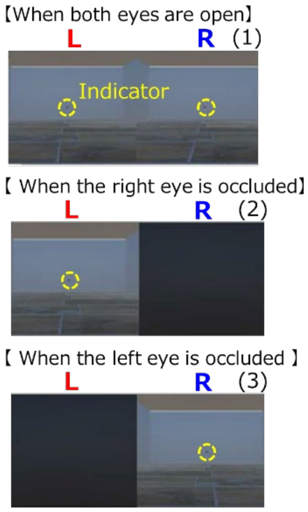

Fig.4 Image as it appears to the examinee during the Cover-Test

4.4 Procedure for calculating the magnitude and directions of ocular misalignment

This section describes how we implement our system: using data from section 4.2 to describe the procedure for calculating the amount and direction of eye misalignment, up to section 4.3 to determine the presence, type, and magnitude of eye misalignment anomalies.

Fig.5 shows procedures from data collection to the determination of eye misalignment. 4.4.1 to 4.4.10. Below are the detailed explanation for each step. Fig.6 shows the data collection process for ACT/CUT.

4.4.1 collect data on eye movements

Each step in Fig.5 takes three seconds: collecting 90 sets of eye data per second. We use only the x and y coordinates of the three-dimensional corneal apex in the calculations. Since the depth of the corneal apex position (synonymous with eye position) changes only slightly during the examination, we ignored the z coordinates in the current system.

4.4.2 removal of invalid frames

We may not obtain valid data due to reasons such as blinking. We call these invalid frames and replace the corneal vertex coordinates with (0,0,0) to exclude the eye data from the calculation.

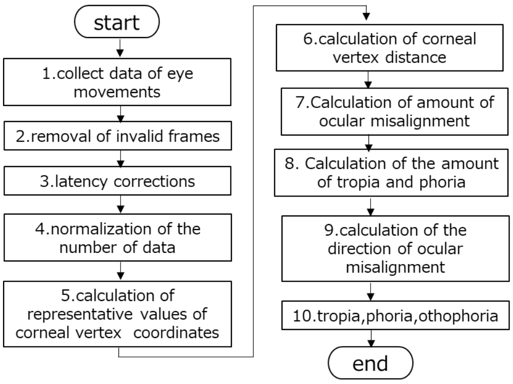

Fig.5 calculation of the amount and direction of ocular misalignment

4.4.3 latency corrections

Fig.6 shows the horizontal eye movements during the cover test. The eye-response lag is called latency (see Fig.6). If the eye data immediately after cover/uncover is used to calculate the prismatic volume without considering the latency, the reliability of the calculation results may decrease. However, latency varies with age and individual characteristics. In our study, we determined that latency refers to the time between the moment of cover/uncover and the point of maximum eye movement. We excluded all eye data collected during this interval.

4.4.4 normalization of the number of data

ACT			CUT		
Ph.	left eye	right eye	Ph.	left eye	right eye
0	uncover	uncover	0	uncover	uncover
1	uncover	cover	1	uncover	cover
2	cover	uncover	2	uncover	uncover
3	uncover	cover	3	cover	uncover
4	cover	uncover		⋮	⋮
5	uncover	cover			
6	cover	uncover	9	uncover	uncover
7	uncover	cover	10	uncover	cover
8	cover	uncover	11	uncover	uncover
9	uncover	uncover	12	cover	uncover

Fig.6 The state of the eye during the ACT/CUT examination phases

Although the number of data obtained at each step is not constant due to preprocessing delays, it is desirable to have a constant number of data used in the decision-making process to improve the calculation accuracy. Therefore, we divide each step into N parts. And the data used for judgment is obtained by dividing the data points into N parts.

4.4.5 calculation of representative values of corneal vertex coordinates

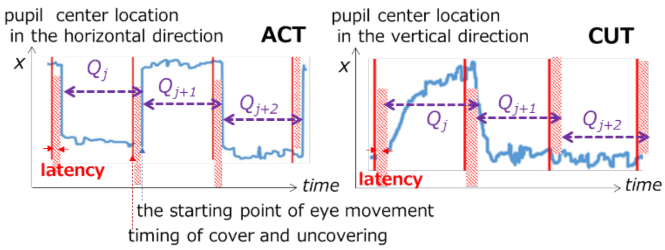

Fig.7 eye movement and response delay at the time of cover and uncovering

In ACT, we calculate the average as a representative value of the eye position data in each step (see Q_j, Q_{j+1} and Q_{j+2} in Fig.7-ACT) to determine the amount of eye movement due to cover/uncover.

We obtain the average eye position in step j $(\overline{x_j}, \overline{y_j})$ using the position data of the eye in frame 1 in step j using the following formula:

$$\overline{x_j} = \frac{1}{N}\sum_{i\in Phase j} x_i$$

$$\overline{y_j} = \frac{1}{N}\sum_{i\in Phase j} y_i$$

Eye movement is slower in CUT than in ACT. Therefore, CUT used the eye position at the peak of each step itself as the representative value(see Q_j, Q_{j+1}, Q_{j+2} in Fig.7-CUT).

4.4.6 calculation of corneal vertex distance

The amount of eye movement during cover and uncover is the distance between the representative value of the eye position in the step before cover/uncover and the representative value in the later step.

4.4.7 Calculation of the amount of ocular misalignment

For example, as shown in Fig.6, if the apex of the cornea, the origin coordinate of the line of sight, moves from point a to point b, we approximate the distance the eye has moved as the linear distance between a and b. To find the size of the angle θ facing side ab, first, draw a perpendicular line from point b to a straight line passing through point b and rotation point P, which is the center of the rotational movement of the eyeball. A right-angled triangle Pba' is formed with a' as the point where this line intersects the straight line passing through the two points P and a. The distance between ba' is approximated by the distance between ab, and we calculate the amount of eye misalignment θ by applying the following formula.

$$\theta = tan^{-1}\left(\frac{m}{13}\right) \times \frac{180}{\pi}$$

The number 13 represents the distance between the point of rotation (P) and the corneal apex (b). This measurement is 13mm, regardless of age or gender [14].

4.4.8 Calculation of total deviation, tropia, and phoria

We calculate everything with the method in Section 4.4.7. In the example of Fig.1, we detect the ocular deviation (ms + mp) by ACT and find the angle opposite to it. The amount of tropia and phoria is determined by detecting the ocular deviations ms and mp by CUT and finding the corresponding angle.

4.4.9 calculation of the direction of eye misalignment

We use the left eye as the criterion for determining the direction of strabismus. We determine the average amount of movement when the left eye is occluded and judge the direction of the strabismus by its sign. Horizontally, the assumption is that the shift to the ear is negative and the shift to the nose is positive. When assessing eye alignment, a negative result is indicative of exotropia, while a positive result suggests esotropia. Vertically, a downward shift is negative, which we judge as hypophoria, and an upward shift is positive, which we judge as hyperphoria.

4.4.10 Determination of tropia and phoria

If the total deviation is 1*Δ* or more, the examinee has either tropia or phoria. If the amount of ocular deviation is 1 *Δ* or more, it is tropia; if it is less than 1 *Δ* and the amount of obliquity is 1 *Δ* or more, it is phoria. We will discuss the numerical units (*Δ*) in the next section.

4.5. System Performance Evaluation Methods

In section 3.2, we performed the Maddox test and evaluated the performance by taking the total deviations obtained as the actual value. First, we examined the correlation between the total deviations obtained by the ACT and the results of the Maddox test total deviations. We also examined the correlation between the sum of the amounts of tropia and phoria and the total deviation. We then examined the consistency between the respective inspection result values and those of Maddox. Maddox collects numerical values in prism dioptres (*Δ*), so the system converts the amount of eye position deviation (θ in Fig. 8) into the prism amount P(θ) and evaluates it. Since the unit of the numerical values obtained by Maddox is prism dioptres (*Δ*), the amount of deviation of the eye position by the system (θ in Fig. 8) is converted to the prism amount P(θ) and evaluated. As 1 *Δ* is equal to 0.57 (deg), we convert it into the following formula [14]:

$$P(\theta) = \frac{\theta}{0.57}$$

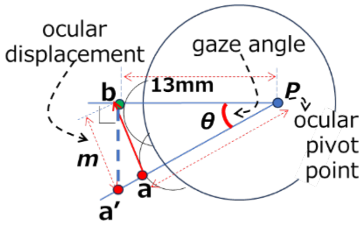

Fig.8 Relation between eye movement distance and prism amount

5. Verification experiment

5.1. *Experimental details*

By comparing the results with the correct results obtained by the Maddox test, we evaluated the system's performance on 16 subjects.

5.2. Evaluation / Consideration

5.2.1 ACT

Table 1 shows the actual values for the total deviation in the horizontaldirection (x) in ACT for both the proposed system and the Maddox test.

Different methods of processing outliers yield the values in (a), (b), and (c). (a) deletion of the top and bottom 10% of each phase; (b) deletion based on the interquartile range of each phase; and (c) replacement of the eye position's mean value with the median. The table is labeled XT/XP for exotropia/exophoria and ET/EP for esotropia/esophoria. We rounded the values to the third decimal place of the prism equivalent of the ocular position deviation. Those diagnosed with exotropia/exophoria are in blue; those with esotropia/esophoria are in red.

Table 2 shows the evaluation results for the measured data in Table 1. We evaluated three factors: the mean error of all deviations, the correlation coefficient, and the significant difference. In the following, we discuss the results without outlier treatment. The average error is 0.61 *Δ*, less than 1 *Δ*, indicating that the system's value was close enough to Maddox's actual value. We display the results for the nine examinees who scored an abnormal value of 1 *Δ* or higher on the correct Maddox test in Fig. 9-ACT to enhance clarity. Blue shows Maddox's correct results, whereas orange represents the suggested system's outcomes. The Spearman's rank

Table.1 measured value of a total amount of deviation

examinee	Maddox	Proposed system (a)	(b)	(c)
A	0-1ET/EP	0.87ET/EP	0.88ET/EP	0.89ET/EP
B	0	0.54XT/XP	0.55XT/XP	0.54XT/XP
C	0	0.44ET/EP	0.40ET/EP	0.41ET/EP
D	1XT/XP	1.30XT/XP	1.50XT/XP	1.35XT/XP
E	0	0.54XT/XP	0.55XT/XP	0.56XT/XP
F	4XT/XP	3.96XT/XP	4.14XT/XP	3.98XT/XP
G	0	1.07ET/EP	1.09ET/EP	1.08ET/EP
H	1XT/XP	0.98XT/XP	1.02XT/XP	0.98XT/XP
I	1-2ET/EP	2.37ET/EP	2.57ET/EP	2.38ET/EP
J	0	0.46XT/XP	0.37XT/XP	0.47XT/XP
K	0	0.29ET/EP	0.30ET/EP	0.32ET/EP
L	8ET/EP	9.25ET/EP	9.37ET/EP	9.27ET/EP
M	1XT/XP	0.64XT/XP	0.55XT/XP	0.65XT/XP
N	10-12XT/XP	12.55XT/XP	12.53XT/XP	12.52XT/XP
O	1XT/XP	1.49XT/XP	1.67XT/XP	1.71XT/XP
P	8ET/EP	7.95ET/EP	8.02ET/EP	9.71ET/EP

Table.2 Test results of Table 1

	outlier without process	(a)	(b)	(c)
mean error	0.610	0.550	0.590	0.660
correlation	0.956	0.957	0.956	0.944
p value (bilateral probability)	2.11×10^{-4}	2.15×10^{-4}	2.56×10^{-4}	2.14×10^{-4}

correlation coefficient is 0.956. This implies a solid correlation with the actual value. The null hypothesis is "H0: (Maddox's) true scores are uncorrelated with the proposed system's scores". The alternative hypothesis is "H1: we correlate the actual values with the resulting values from the system." As a result, the p-value was 2.11 x 10-4 (< 0.01). The values were not significantly different from the actual ones. From the above, we can see that the results of quantifying the horizontal (x) direction in the ACT in the proposed system have a solid correlation with Maddox's actual value. Furthermore, there was almost no difference in assessment outcomes between data with and without outlier processing. This means that processing the data did not lead to a significant improvement in accuracy.

5.2.2 CUT

Table 3 shows the amount of tropia and phoria, the total deviation in the horizontaldirection (x) by CUT using the proposed system, and the actual total deviation by Maddox. CUT calculates the total deviation by adding the amounts of tropia and phoria, rather than using the directly measured amounts of eye deviations as in ACT. The view of other tables is the same as in 5.2.1.

Table 4 shows the evaluation results for the measurement data in Table 3. We discuss the results without outlier processing below. First, the average error of all deviations is 1.50 Δ, which is higher than 1 Δ. Therefore, it is hard to say that this result is close enough to the actual value. The graph in Fig. 9-CUT shows that although the values of the system have a considerable error compared to those of the Maddox, we can confirm the consistency of the relationship between the large and small values. Spearman's rank correlation coefficient is 0.810, indicating a strong correlation. In addition, the p-value based on the null and alternative hypotheses is 1.71 × 10-3 (< 0.01), which is not significantly different. The errors for the data with outlier treatment were slightly higher than

Table.3 measurements of strabismus and obliquity

examinee	Maddox	Proposed system: strabismus amount(a)	phoria amount(a)	the total derivation(a)	strabismus amount(b)	phoria amount(b)	the total derivation(b)
A	0	0.11EP	0.70EP	0.81ET/EP	0.21ET	0.60EP	0.81ET/EP
B	0	0.41XT	0.40XP	0.81XT/XP	0.30XT	0.56XP	0.86XT/XP
C	0	0.60XT	0.70XP	1.30XT/XP	0.60XT	0.79XP	1.39XT/XP
D	1XT/XP	0.54XT	0.97XP	1.51XT/XP	0.56XT	0.94XP	1.50XT/XP
E	0	0.41XT	0.43XP	0.84XT/XP	0.30XT	0.55XP	0.85XT/XP
F	4XT/XP	0.75XT	1.71XP	2.46XT/XP	0.79XT	1.71XP	2.50XT/XP
G	0	0.19ET	1.14EP	1.33ET/EP	1.14ET	1.10EP	1.24ET/EP
H	1XT/XP	0.23XT	0.65XP	0.88XT/XP	0.25XT	0.67XP	0.98XT/XP
I	1-2ET/EP	0.43ET	1.24EP	1.67ET/EP	0.55ET	1.24EP	1.79ET/EP
J	0	0.20XT	0.93XP	1.13XT/XP	0.11XT	1.01XP	1.12XT/XP
K	0	0.28ET	0.25EP	0.53ET/EP	0.19ET	0.35EP	0.54ET/EP
L	8ET/EP	0.72ET	4.72EP	5.44ET/EP	0.74ET	4.62EP	5.36ET/EP
M	1XT/XP	0.91XT	1.13XP	2.04XT/XP	0.97XT	1.16XT	2.13XT/XP
N	10-12XT/XP	0.62XT	11.08XP	11.70XP	0.58XT	11.04XP	11.62XT/XP
O	1XT/XP	1.10XT	1.50XP	2.60XT/XP	0.73XT	1.75XP	2.60XT/XP
P	8ET/EP	9.19ET	9.52EP	18.71ET/EP	9.17ET	9.52EP	18.69ET/EP

Table.4 Test results of Table 3

	outlier without process	(a)	(b)
error(Δ)	1.500	1.530	1.580
correlation	0.810	0.924	0.926
p value (bilateral probability)	1.71×10^{-3}	3.33×10^{-4}	3.33×10^{-4}

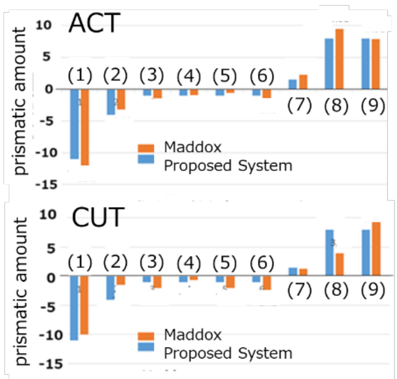

Fig.9 Consistency between the system's prism amount and Maddox's prism amount

those without. The correlation coefficients improved. However, there was only a slight improvement in accuracy.

In summary, ACT showed high accuracy, and CUT showed relatively good accuracy. Therefore, we are confident that we have showcased the practicality of our suggested approach and system.

6. Conclusion

We have developed an eye misalignment detection system that can perform the Cover-Test, an eye position examination method, in a small space without being affected by the examiner's skill or the examinee's cognitive ability. We created a virtual examination space using VR technology. To identify the position of the pupils, we displayed an optotype within the environment and recorded their movements while conducting the cover uncover test. We have automated a series of processes that involve measuring values. They automatically calculate the ocular deviation, convert it into numerical data, and obtain the results. As a result, the issues of previous studies, such as the influence of eyelid and eyelash movement and examination room lighting on the accuracy of the examination, have been eliminated. Furthermore, the HMD is more comfortable to wear than the 3D glasses used in the previous study. It also reduces stress on the examinee, thus improving usability.

We evaluated the system by comparing the calculation results with those of the Maddox test, a conventional clinical test. The accuracy of the CUT, which requires the detection of smaller abnormal amounts, was not as successful as that of the ACT, although we confirmed the consistency with the results, the actual values, of the Maddox test, and the overall accuracy was relatively good.

There are four future issues.

First, devise to improve CUT's inspection accuracy.

Second, to distinguish orthophoria from minor abnormalities. Even without abnormalities, when performing a cover test, the eyes make miniature movements known as fixational eye movements. As a result, determining the existence of a tiny anomaly is frequently quite challenging. The system's goal is to detect such anomalies. The necessity for this judgment itself is not clinically high. We believe that the information collected in developing such an extremely accurate system that can make this assessment will promote the development of other systems employing VR.

Third, to enable the accurate measurement of vertical eye deviation. As shown in this paper, there is a possibility that the current system can measure the deviation in the horizontal direction with high accuracy. Because of the scarcity of data on examinees with severe vertical abnormalities, measurement accuracy in the vertical direction remains unknown. The most critical short-term challenge is gathering vertical anomaly data and assessing its accuracy.

The fourth is to develop a system that makes the test easy to perform, even when the examinee is only three years old. This will allow early detection of congenital tropia and phoria.

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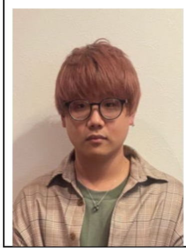
Authors Introduction

Kayoko Takatsuka

She is an Expert technical staff with the Faculty of Engineering, University of Miyazaki, Japan. She graduated from Kumamoto University, Japan, in 1992 , and the Ph D. degree in interdisciplinary graduate school of agriculture and engineering from University of Miyazaki, Japan, in 2014. Her research interest is process systems engineering

Yoki Nagatomo



He was received the B. E degrees in computer science and system engineering from Miyazaki University, Miyazaki Japan, in 2022. He is now a master course student of Miyazaki University. His research interest virtual realit

Noriyuki Uchida

He is an orthoptist. He is currently a Doctoral course student in Miyazaki University, Japan. His research interests include visual optics, strabismus and amblyopia.

Takuya Ikeda

He was received the M. E degrees in computer science and system engineering from Graduate school of Miyazaki University, Miyazaki Japan, in 2021. His research interests virtual reality.

Masayuki Mukunoki

He is now a Professor of Faculty of Engineering at University of Miyazaki in Japan. He received the bachelor, master and doctoral degrees in Information Science from Kyoto University. His research interests include computer vision, pattern recognition and video media processing.

Naonobu Okazaki

He received his B.S, M.S., and Ph.D. degrees in electrical and communication engineering from Tohoku University, Japan, in 1986, 1988 and 1992, respectively. He joined the Information Technology Research and Development Center, Mitsubishi Electric Corporation in 1991. He is currently a Professor with the Faculty of Engineering, University of Miyazaki since 2002. His research interests include mobile network and network security. He is a member of IPSJ, IEICE and IEEE.