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Assessing Visual Fatigue of Welding Mask Wearers Through Infrared Imaging-Based Ocular Feature Analysis

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Sangmyung University Institutional Review Board under Application IRBSMU-S-2021-1-005, and performed in line with the Declaration of Helsinki.

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ABSTRACT Electronic devices have become indispensable to individuals today. Looking at these electronic displays for extended periods causes visual fatigue. Herein, we propose three metrics for objective and quantitative measurement of visual fatigue: blink frequency, blink duration, and pupil accommodation speed. After taking eye images using an infrared camera, binarization and contour detection were performed to localize the pupil. The diameter of the localized pupil region, defined as pupil size, was calculated based on the number of black pixels in the pupil region. The blink frequency, blink duration, and pupil accommodation speed were measured by analyzing successive pupil sizes. To obtain pupil accommodation speed, inflection points were extracted after removing high frequency elements in the frequency domain. After inducing visual stimulation on 10 participants by welding sparks for 30 minutes, two incremental fatigue periods were observed. Blink frequency and duration increased in a similar manner, and pupil accommodation speed decreased in the sections. Therefore, it can be confirmed that as the degree of visual fatigue increases, blink frequency and duration increase, and pupil accommodation speed decreases. Moreover, we confirmed that when eyes become tired, the tendency of blink frequency and duration is opposite to that of the pupil accommodation speed.

INDEX TERMS Blink duration, blink frequency, fast Fourier transform, pupil accommodation speed, visual fatigue.

I. INTRODUCTION

Electronic devices, such as smartphones, televisions, and tablets have become indispensable to a lot of modern people. Besides, watching electronic displays for a long period causes visual fatigue. Since people spend more time using electronics than before, decreasing visual fatigue has become an important issue in the electronic display industry [1].

To reduce visual fatigue, it needs to be measured accurately first. There have been several studies conducted to quantify visual fatigue. Despite various methods, there are still limitations and inconveniences when using existing methods. Therefore, we propose a new assessment of visual fatigue based on the characteristics of pupil movement and pupil size. The pupil size changes with the relaxation and contraction of the iris, according to visual and emotional factors. According to a previous study, muscles become slower when they are tired and pupil accommodation speed slows down as visual fatigue increases [2]. In another research, three ophthalmic features (blink frequency, eye-closed duration, and pupil accommodation speed) were used to objectively measure visual fatigue [3]. Experiments were done using three different stimuli, such as gamma conversion, color temperature conversion, and brightness conversion to the eyes. Results showed that gamma modification induces the most visual fatigue. Moreover, based on research that eyes become more tired with the increase in blink frequency, it can be seen that eyes become tired as blink duration increases. Therefore, we carried out a study based on the hypothesis that the tendency of blink frequency

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TABLE 1. Summarized comparisons of previous and proposed methods to measure visual fatigue.

Category	Method	Advantages	Disadvantages
Not using eye features	Questionnaire [4][5]	Easier and faster acquisition than other sensor-based and eye tracking-based methods	Results can be subjective to users.
	Biological signals [6][7][8]	More objective compared to questionnaires	- Cause discomfort to user because of attachment of sensors to body - Data from attached sensors are affected by minimal movement
Using eye features	Eye tracker [9][10]	More comfortable than biological signals because no sensors are attached	Eye tracking device and effort to build an experimental environment are still required
	Biological signals and eye tracker [11]	Higher accuracy of visual fatigue measurement than single-modality methods	- Cause discomfort to user because of attachment of sensors to body - Data from attached sensors are affected by minimal movement
	Questionnaire and eye tracker [12]	- Higher accuracy of visual fatigue measurement than single-modality methods. - More objective than single-modality questionnaire methods	Subjective results from questionnaire and objective results from eye tracker can be contradictory.
	Multiple eye features (proposed method)	Less discomfort to users and only an infrared camera is required	Lower accuracy of visual fatigue measurement than multiple-modality methods

and duration is opposite to that of pupil accommodation speed.

For a more convenient and objective measurement in a real-world environment, we propose quantitative metrics based on characteristics of pupil movement and size. Blink frequency, blink duration, and pupil accommodation speed were used as objective indicators of visual fatigue. Using multiple indicators instead of one is likely to yield better results in the visual fatigue analysis. In the proposed method, pupil images are captured by an infrared camera, and analyzed to assess the degree of visual fatigue. Without using any sensor or inducing any stimulation, real-time visual fatigue analysis was possible.

II. RELATED WORKS

Existing methods to measure visual fatigue vary from studies due to the absence of well-defined criteria. Many previous studies focus on measuring visual fatigue, and their methods are classified as either with or without eye features.

There are two methods to assess visual fatigue without using eye features. One method is using questionnaires when assessing visual fatigue [4], [5]. Although it is quite easy to make questions, evaluations are personal and may be subjective. The other method is using biological signals, such as electroencephalography (EEG), electrocardiogram, electrooculography, and photoplethysmogram [6]–[8], which are objective compared to questionnaires. Although many kinds of biological signals are used to measure fatigue, there are some disadvantages. It can cause inconvenience to users in that the sensors need to be attached to the body. Also, attached sensors are so sensitive that results can be affected by even a small amount of movement.

Second, eye feature-based methods include using pupil features, such as pupil movement or pupil size via eye trackers [9], [10]. Although the used of an eye tracker is an objective method, it requires devices and considerable effort to build an experimental environment. Other studies used multiple modality-based methods. EEGs and blinking rate considering a Bayesian network were used to measure visual fatigue [11]. These methods can have higher accuracies than single modality-based methods, but there is still discomfort due to biological signal sensors. In another study [12], the authors used a questionnaire as a subjective evaluation tool and a blinking rate as an objective evaluation tool to assess visual fatigue when viewing two-dimensional (2D) and three-dimensional (3D) images. As a result, a high correlation was identified between the questionnaire and blinking rate, and the R-squared value was between 0.87 and 0.93. This shows that the more tired the eyes are, the higher the blinking rates would be. Table 1 summarizes the comparisons of previous and proposed methods to measure visual fatigue.

III. PROPOSED METHOD

A. EXPERIMENTAL SETUP

Most studies have compared visual fatigue when watching 2D and 3D videos. Visual fatigue when watching 3D videos is caused by the inconsistency between lens accommodation and convergence [13]. Lens accommodation and convergence are important systems in human vision. Accommodation is the ability of the eye to change its focus between distant and near objects by lens shape changes. For example, the lens becomes thinner when looking at distant objects, and the lens thickens when looking at close objects. Convergence is the ability to turn the two eyes inward toward each other to look at a close object. Although there are some reports that people experiencing visual fatigue and dizziness when watching 3D videos, the intensity of the fatigue differs from person to person [14]. Therefore, in this study, we used short and repetitive changes in brightness to induce visual fatigue. The iris is a thin, annular structure in the eye, responsible for controlling the pupil diameter and size, and the amount of light reaching the retina [15]. Based on the principle, welding sparks were used to induce visual fatigue, such as eye pain and visual stress, to reduce individual differences.

Welding is a technique for attaching two identical or different metals by applying high heat, and welding sparks are generated by an arc phenomenon. The arc phenomenon is a continuous flaming discharge phenomenon between the insulating materials. Welders must wear protective gears to protect themselves from welding flames that emit very intense light and heat. If protective gears are not worn properly, it is possible to have photokeratitis, an inflammation of the cornea due to the light.

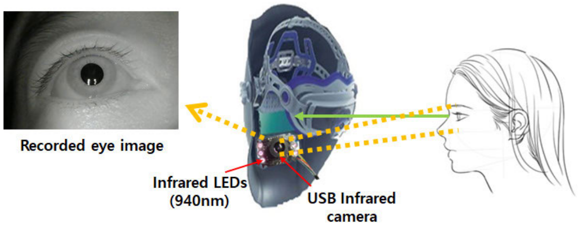


FIGURE 1. Experimental equipment setup.

Fig. 1 represents how the experimental equipment was set in this study. While the participants looked at welding sparks through a green screen, eye images were recorded by an infrared camera. The infrared camera was attached to the interior of a welding mask to estimate the visual fatigue caused by the welding sparks in the left eye. Given that the camera was attached to the welding mask, eye images could be acquired without being affected by the facial movements. The camera transmitted images at 30 frames per second with an HQCAM infrared USB camera that passed infrared rays with wavelengths above 750 nm. The wavelength of the infrared illumination used was 850 nm, and it had a wavelength band that could pass through the camera lens to obtain a clear eye image. While participants stared at welding sparks, a welder standing next to them controlled the welding sparks. The welding mask used in the experiment was an ACEW+ model [16], and for safety, all participants and welder wore a welding mask.

The experiment involved 10 participants who wore a welding mask and stared at welding sparks. The participants stared at the welding sparks for 30 seconds, and then rested for 30 seconds, repeating this cycle for 30 minutes as shown in Fig. 2(c). Fig. 2(a) shows when participants are staring at welding sparks, Fig. 2(b) shows when they are resting. While the eyes could recover during a 30-second break, full recovery might not be achieved. Since staring at welding sparks for 30 minutes without any break can harm the eyes, we included a 30-second break during experiments. We conducted experiments inducing temporary fatigue, without any permanent harm to the eyes. Also, welders take a break in the middle of work in an actual welding environment.

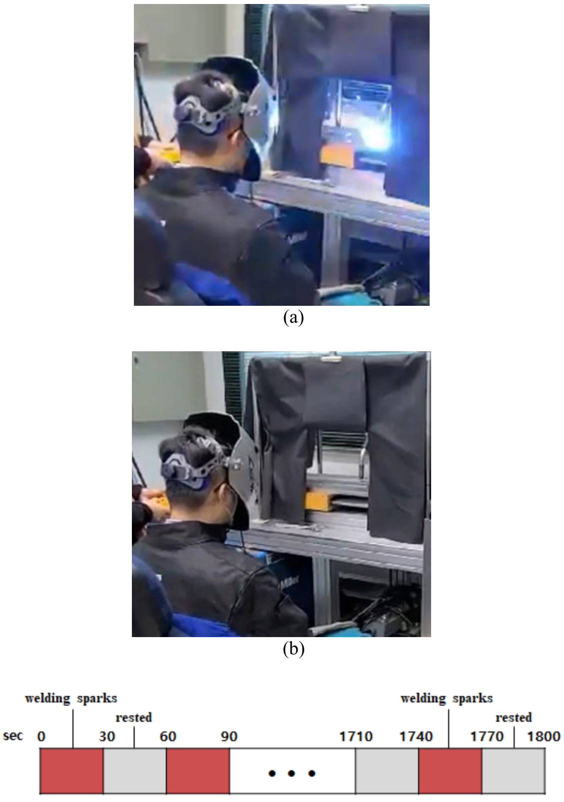


FIGURE 2. An experiment using welding sparks to induce visual fatigue in the participants. (a) Wearing a welding mask and staring at welding sparks. (b) Taking rest without any visual stimulation. (c) Experimental timeline.

All subjects gave their informed consent for inclusion before participation. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the ethics committee of Sangmyung University Institutional Review Board (IRB-SMU-S-2021-1-005). Based on the 13-1-3 system of the Enforcement Regulations of the Act on Bioethics and Safety of the Republic of Korea, ethical review and approval were waived (IRB-SMU-S-2021-1-005) for this study by Sangmyung University Institutional Review Board, because this study uses only simple contact measuring equipment or observation equipment, without any physical changes.

B. PUPIL DETECTION

To assess visual fatigue induced by welding sparks, it is necessary to gain information on pupil size through accurate pupil detection. The pupil size detection algorithm used in this study comprised four steps as shown in Fig. 3.

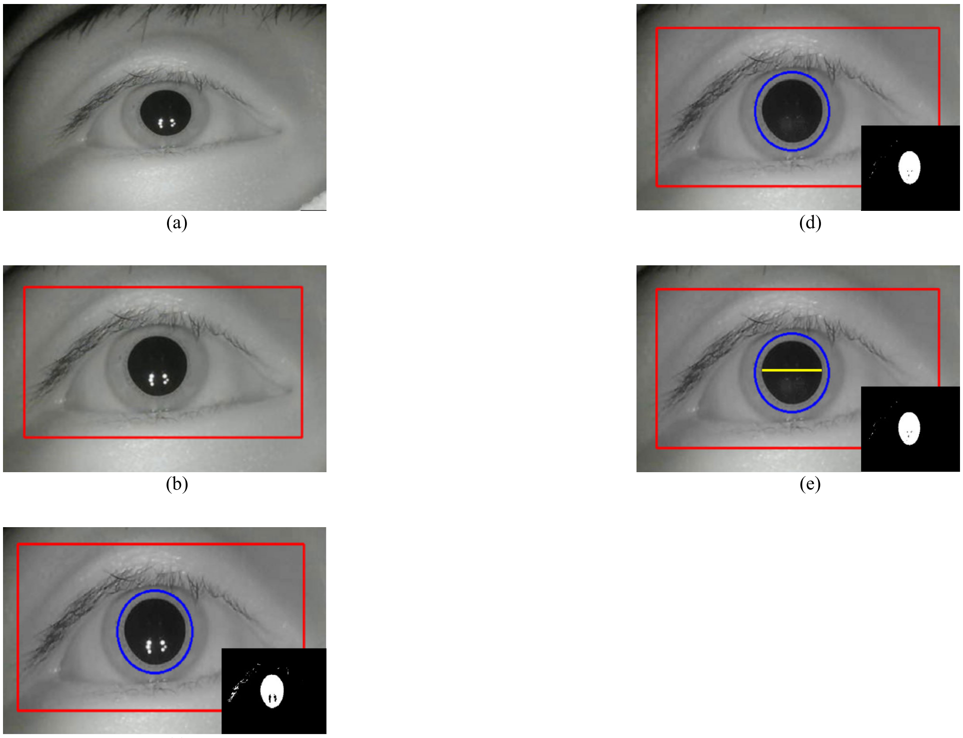


FIGURE 3. **Process of the proposed pupil size calculation algorithm. (a) Captured image from experimental videos; (b) Manually defined region of interest (red box); (c) Pupil candidates after binarization and geometric filtering (blue circle); (d) Removal result of specular reflection; (e) Calculation result of a diameter as pupil size (yellow solid line). Black-and-white images in the bottom right corner show binarization of color images.**

Captured eye images were extracted from experimental videos. After cropping eye regions manually, binarization and contour detection were performed on eye images. For a pupillary region to be included, the following two conditions were checked: first, pupil size of $\geq$ 70 pixels when seen virtually. Although the pupil size is different from person to person, we could calculate the average pupil size of the participants by recording the eyes from the same distance. Pupil size was calculated by counting the number of black pixels in the pupil region. Secondly, using the fact that the shape of the pupil region is circular, the aspect ratio of the pupil region must (be bigger than 0.8 and smaller than 1.2) exceed 0.8 and must not exceed 1.2. The aspect ratio was calculated by dividing the pupillary width by the pupillary height.

Fig. 3(d) shows the results after removing specular reflections caused by infrared light. Finally, the pupil size is indicated by the yellow solid line in Fig. 3(e). It was calculated by considering the row with the highest number of black pixels in the pupil area as the diameter of the pupil. The pupil size was calculated at every frame, and 54,000 pupil sizes were obtained from the 30 min experiment.

C. VISUAL FATIGUE ANALYSIS

Fig. 4 is a flow chart showing the process of the visual fatigue analysis proposed in this study. After pre-processing and calculating the pupil size from pupil images obtained from an infrared camera, the three quantitative metrics of visual fatigue were calculated. Fig. 5 shows the detailed process of removing noise to calculate pupil accommodation speed (f_3) in Fig. 4.

To calculate the blink frequency and duration using the calculated pupil size, it is necessary to detect frames where the pupil size is zero. The pupil size is defined as a diameter of the localized pupil. Pupil size detection is dependent on experimental environments, such as the humidity of a welding mask or the condition of the subjects. Therefore, interpolation was performed on the pupil size calculation for more accurate results. Blink frequency is the number of frames in which the pupil size becomes zero from a non-zero frame, and blink duration is the number of frames where the pupil size is zero.

$$f_1 = \sum_{n=1}^{N} B_n$$

$$B_n = \left\{ \begin{matrix} 0 \\ 1(P_n \neq 0 and P_{n+1} = 0) \end{matrix} \right\} \tag{1}$$

$$f_2 = \sum_{n=1}^{N} D_n$$

$$D_n = \left\{ \begin{matrix} 0 \\ 1(P_n = 0) \end{matrix} \right\} \tag{2}$$

$$f_3 = \frac{1}{M} \sum_{m=1}^{M} \left| \frac{P_{Z_{m-1}} - P_{Z_m}}{F_{Z_{m-1}} - F_{Z_m}} \right| \tag{3}$$

We calculated visual fatigue using blink frequency, duration, and pupil accommodation speed, according to

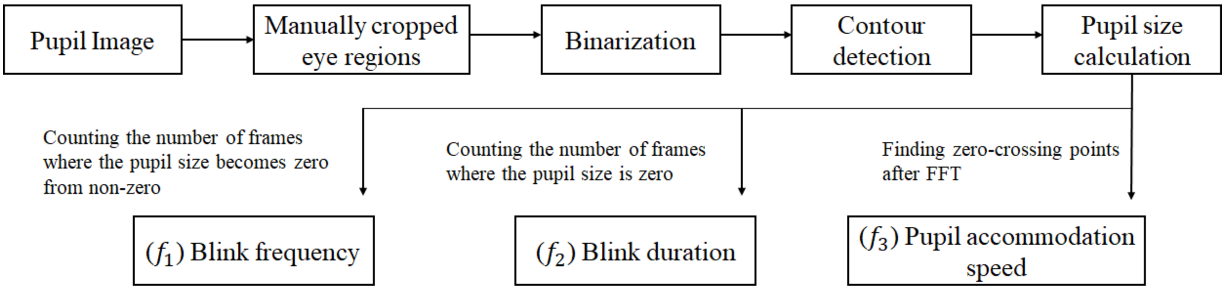


FIGURE 4. A flow chart of the proposed visual fatigue calculation process.

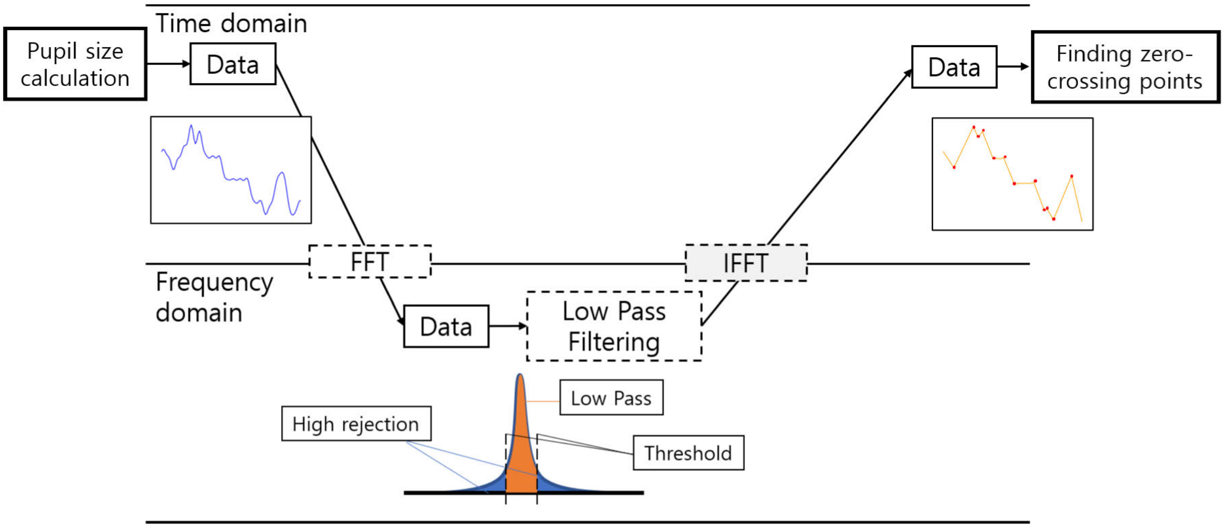


FIGURE 5. The process of finding zero-crossing points from the calculated pupil size in Figure 4.

Equations (1) through (3). In Equation (1), B_n means the total number of blinks during N, while N is the total number of frames during a specific section (set to 3 minutes in this paper). P_n is the diameter of the pupil region detected in the nth frame. When a pupil is detected in the current frame ($P_n \neq 0$) and the pupil size becomes 0 in the next frame ($P_{n+1} = 0$), we assumed that the eye blinked at the nth frame. In Equation (2), D_n is the number frames when eyes are closed ($P_n = 0$). Total blink duration for N frames is calculated by summing up D_n for N frames.

The results of pupil size calculation were also used to calculate pupil accommodation speed. In Fig. 6, the blue line indicates the pupil size per frame, showing three seconds from an experimental video. There was noise, such as a slight vibration or an incorrect value, in the original signal. Therefore, we used a fast Fourier transform (FFT) to effectively remove the noise. Using FFT from the Python library, the pupil size per frame was converted from a time domain into a frequency domain. To remove noise, which is a high-frequency component, high-frequency signals above the set threshold were removed. Then, the resulting signals were converted into a time domain from a frequency domain using inverse FFT from the Python library. In Fig. 6, the blue line represents the original signal, and the orange line represents the results after removing the high-frequency noise. Fig. 7 shows the frequency band and power converted from the original signal, which is the pupil size per frame, using an FFT. Fig. 7(a) through Fig. 7(c) show the results after removing high-frequency signals with thresholds of 0.5, 0.25, and 0.01, respectively. The blue line represents the original signal, and the orange line represents the filtered signal after removing high-frequency signals. To calculate pupil accommodation speed, zero crossing points were used to obtain inflection points from the filtered signals.

The average pupil accommodation speed is calculated according to Equation (3) after obtaining inflection points. M is the number of inflection points during a specific section (set to 3 minutes in this paper), Pz_m is the pupil size at the mth inflection point among M inflection points, and Fz_m is the frame number of the mth inflection point. The pupil accommodation speed is calculated by dividing the difference in pupil size of two inflection points by the frame difference.

IV. RESULTS

A. BLINK FREQUENCY

The average blink frequency of the experiments conducted on 10 people, measured for 30 min, is shown in Fig. 8. The entire video was analyzed by dividing it into 10 sections of 3 min each.

In Fig. 8, the blink frequency increased in section 4 (9∼12 mins) compared to section 3 (6∼9 mins) and in section 7 (18∼21 mins) compared to section 6 (15∼18 mins).

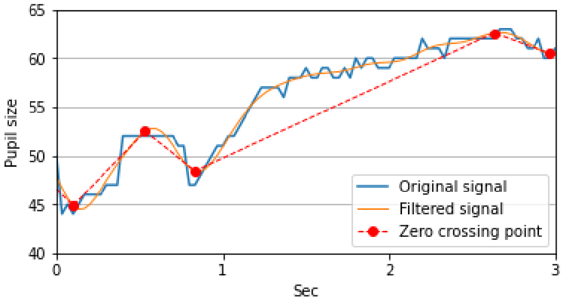
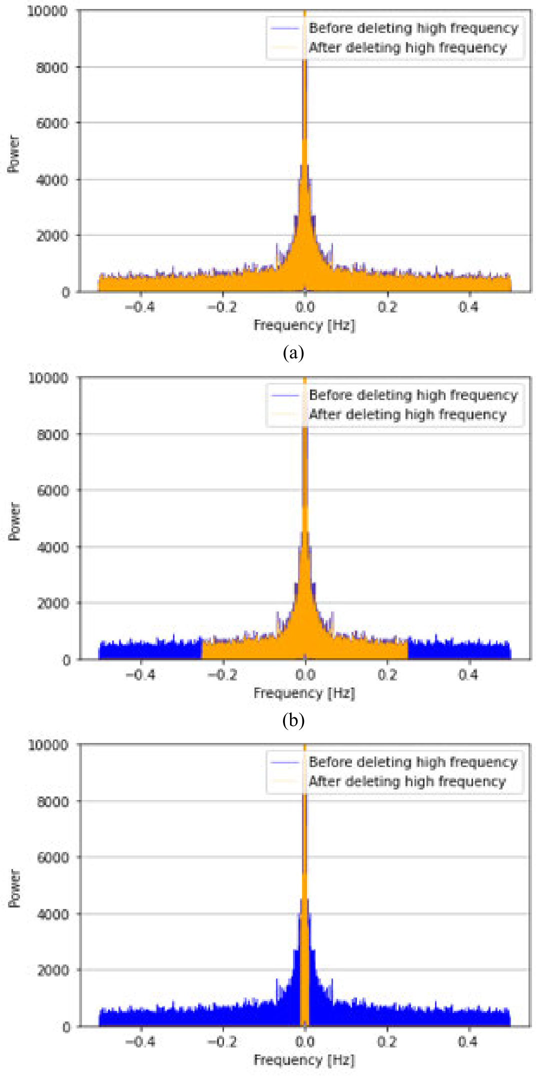


FIGURE 6. **Part of the pupil size after filtering.**



(a)

(b)

(c)

FIGURE 7. **Frequency bands obtained through fast Fourier transform: (a) threshold = 0.5; (b) threshold = 0.25; (c) threshold = 0.01.**

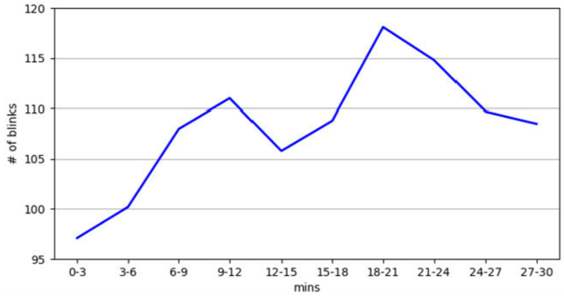


FIGURE 8. **Analysis of average blink frequency.**

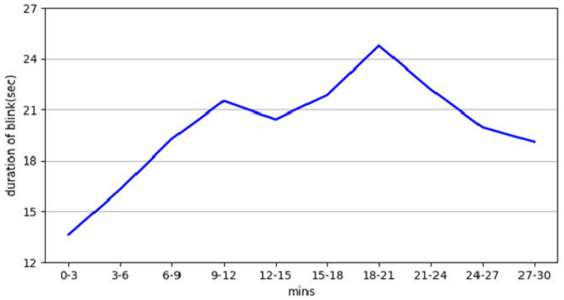


FIGURE 9. **Analysis of average blink duration.**

The blink frequency increased up to 111 times in section 4, decreased to 105 times, and increased again up to 118 times in section 7.

B. BLINK DURATION

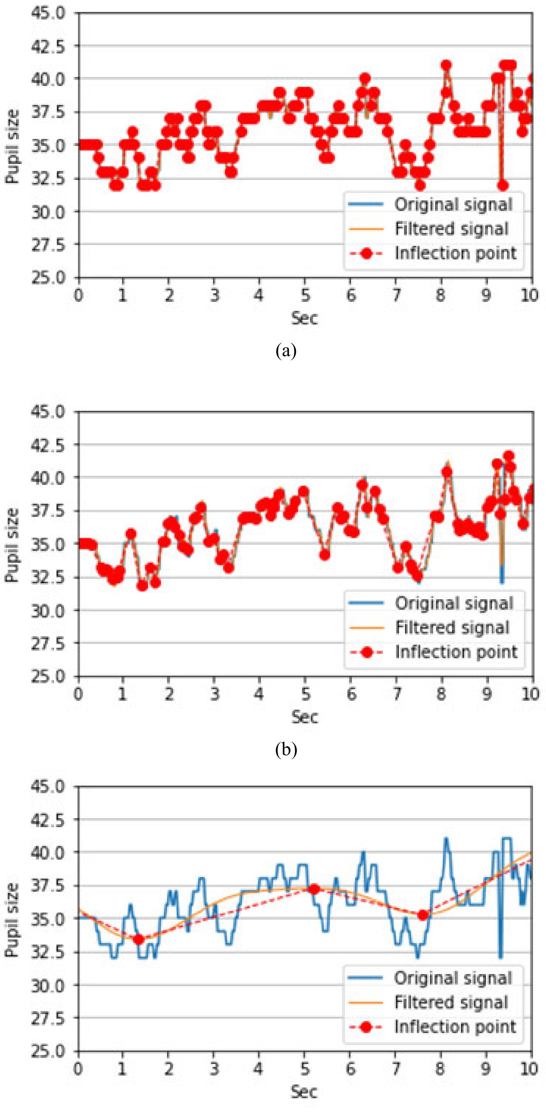
The average blink durations of the 10 participants are shown in Fig. 9. The entire video was analyzed by dividing it into 10 sections, in the same way as described above. The blink duration increased up to 21 seconds in section 4 (9∼12 minutes), decreased slightly, and increased again up to 25 seconds in section 7 (18∼21 minutes). This indicated that two indicators of visual fatigue, blink frequency and blink duration, had similar patterns over time.

According to a previous study [17], the eye blink rate increases as visual fatigue increases, and the increase in blink frequency and duration can be seen as an increase in visual fatigue. Therefore, sections 4 and 7 were referred to as primary visual fatigue and secondary visual fatigue, respectively. Even though visual stimulation was given periodically for 30 minutes, visual fatigue did not seem to increase linearly. Instead, it had an adaptation section after saturation. The result could be because the eyes adapted to the visual stimuli and welding sparks in this study.

C. PUPIL ACCOMMODATION SPEED

Fig. 10 shows the change in the diameter of the extracted pupil region. The threshold values used to remove high-frequency components were 0.5, 0.25, and 0.01 in order from the left. The high-frequency components were removed by using a Fourier transform on the blue line, which was the original pupil size, and then expressed as an orange line through the inverse Fourier transform. The red dots are inflection points on the orange line, and the red dotted line connects them. The inflection points in Fig. 10 varied depending on the threshold values used to remove high-frequency signals. As the camera recorded at 30 frames per second, the graphs represent a total of 10 s from 700 to 1000 frames.

When a threshold value was set too large, the high-frequency signal was not sufficiently removed, as shown in Fig. 10(a), and the signal included much noise when



(a)

(b)

(c)

FIGURE 10. **Pupil sizes calculated using various thresholds (Original signal, Filtered signal, Inflection points): (a) threshold = 0.5; (b) threshold = 0.25; (c) threshold = 0.01.**

calculating the pupil accommodation speed. If many high-frequency components were removed, as shown in Fig. 10(c), it was difficult to calculate the pupil accommodation speed as well. Therefore, to calculate the pupil accommodation speed, an appropriate threshold was determined by analyzing and comparing the original and filtered pupil images. Fig. 10(b) shows the results of removing high-frequency components when the threshold was set to 0.25.

The pupil accommodation speed was calculated through inflection points obtained using the appropriate threshold value above, and the average was calculated every 3 minutes. Fig. 11 shows the average pupil accommodation speed. The pupil accommodation speed neither increased nor decreased linearly. It decreased in section 4 (9∼12 minutes), increased in section 5 (12∼15 minutes), and decreased again in section 6 (15∼18 minutes). These results show that there were two fatigue sections, similar to the fatigue sections for blink frequency and duration. When visual stimulation was continuously administered, the blink frequency and duration increased over time, while the pupil accommodation speed decreased. It was confirmed that pupil accommodation speed had the opposite tendency to pupil blink frequency and duration.

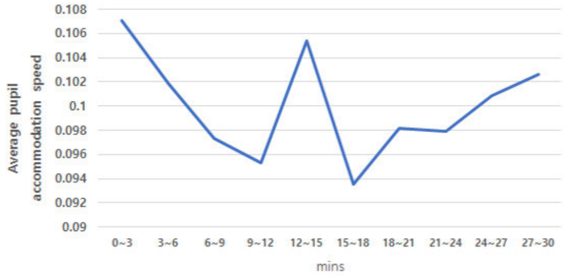


FIGURE 11. **Average pupil accommodation speed with a threshold of 0.25.**

V. DISCUSSION

In this study, we proposed three indicators; blink frequency, blink duration, and pupil accommodation speed, as objective and quantitative methods of assessing visual fatigue. Experiments were conducted on 10 participants in a 30-minutes-long experiment consisting of 30 seconds of visual stimulation and 30 seconds of rest for 30 repetitions. Changes in pupil size were recorded using an infrared camera. Experimental results showed that visual fatigue increased until the first fatigue section in both blink frequency and duration and it decreased or maintained the degree of fatigue in the adaptation section as the eyes adapted to the visual stimulation. In the second fatigue section, visual fatigue increased to the maximum and then decreased again. This shows that visual fatigue does not increase linearly but is adapted to stimulations. This is similar to the results of a previous study [17].

FFT was used to analyze pupil accommodation speed to effectively remove the noise of pupil size changes. After applying Fourier transformation to the original signal, two fatigue sections similar to the results of the blink frequency and duration appeared. In addition, it was possible to prove the hypothesis that the tendency of blink frequency and duration is opposite to that of the pupil accommodation speed. This shows that visual fatigue can be measured using the three objective measurement indicators proposed in this study. Thus, visual fatigue can be accurately measured in real-time.

This study also had limitations. During experiments, participants stared at the welding spark for 30 seconds and rested for 30 seconds. Repetitive stimulation has a limitation, since participants can adapt and predict the stimulation in the latter part of the experiment.

VI. CONCLUSION

Although the experiments in this study were conducted in a welding environment, the proposed indicators are expected to be used for visual fatigue analysis in various fields where visual fatigue is an important issue. In the future, we will overcome limitations by randomly administering stimuli to participants to prevent them from being adopted. We will also use the results of visual fatigue to compare the performance of different welding masks. In addition, if the three indicators proposed in this paper are combined with biological signals and used in a multi-modal method, it will be possible to more accurately measure visual fatigue.

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