An eyewear robot for supporting eyelid closure movement for facial palsy patients

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Yuta Kozaki[1]

***Abstract*—This study proposes a novel eyewear robot for supporting eyelid movements. The robot is designed for people with facial paralysis, especially on one side of the face. People with facial paralysis are not able to blink, which leads to dry eyes and could cause permanent damage to the cornea. They are also prone to developing synkinesis during recovery, and a biofeedback-enabled rehabilitation is considered to prevent it. Based on these, we developed a robot system to support eyelid movements on the paralyzed side, based on the eye closure on the healthy side. The robot has a novel mechanism for supporting the eyelid control, made from soft material, which is called Eyelid Gating Mechanism (ELGM). ELGM deforms by simple rotational or linear actuation inputs and its deformation is customized to eyelid movements. Therefore, this robot can provide non-invasive and gentle support for eyelid movements. In this paper, we present the development and performance evaluation of the developed eyewear robot.**

I. INTRODUCTION

Wearable robots for supporting human motor function have recently been studied worldwide [1]. These robotic technologies are used in medical assistance, military, and even in the field of entertainment. Especially, application for medical assistance has gained considerable attention in recent years. In this field, the main purpose of the robot is to provide physical therapy, enable the semi-automation of therapeutic tasks, and increase repeatability of movements. One of the pioneering works is the robot suit HAL (CYBERDYNE Inc.), which can support human gait functions based on the intention of the wearer, by using surface myoelectric potentials. HAL demonstrated clinical efficiency in medical treatment for stroke or neurological diseases [2] and has recently been covered by insurance programs in Japan, which gives considerable advancement to the social implementation of wearable robotics in medical assistance. In their current state, wearable robots mainly support articulate body joints; however, there are only a few technologies for supporting other body movements like facial movement [3]. For further advancement of the field of wearable robotics, it is important that the robots should be able to support body movements other than articulate body joints.

Human face comprises mimetic muscles that control facial skin and tissues, rather than joints. People with facial paralysis lose the ability to use and control these facial muscles, mostly on one side of the face [4]. As a result, facial muscle loses its tension and gets down, and the patient suffers from severe distractions, such as the inability to blink, make facial expressions, and purse the lips. Because of this, patients may tend to avoid social involvement or try to conceal their faces while interacting with other people. As a result, facial paralysis can decrease the quality of life of the patient significantly.

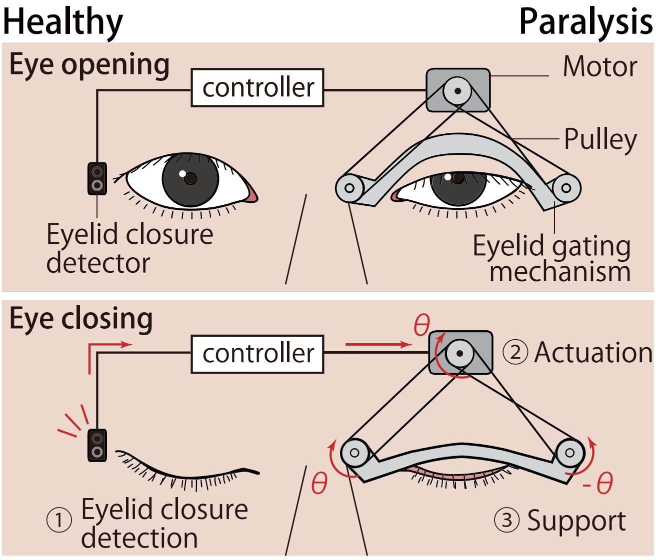

Fig. 1. Overview of the eyewear robot; this robot detects voluntary eye closure on the healthy side and supports the opening and closure movements of the eye on the paralyzed side.

There are some engineering approaches to help people with facial paralysis problems. Senders et al. [5][6] proposed a reanimating eye blink method using an implantable device, which is made of electroactive polymer artificial muscle. Hasmat et al. [7] also proposed a similar method using an implantable device made of a solenoid actuator. Xin et al. [8] proposed an eyelid manipulation method with functional electric stimulation. These approaches are for congenital facial paralysis, and highly invasive methods. Nevertheless, we also proposed a wearable robotic method by using a robotic mask to support the movement of the mouth corner non-ivasively, in order to reconstruct facial expressions [3]. Using myopotential signal of mimic muscles on the healthy side helps reconstitute facial expressions, by pulling the skin on the paralyzed side.

In this study, an eyewear robot was developed to provide non-invasive support for eye opening and closure based on the intention of the wearer. The robot is designed to be used in everyday life to avoid secondary effects related to the inability to blink. Blinking is a receptive movement, which

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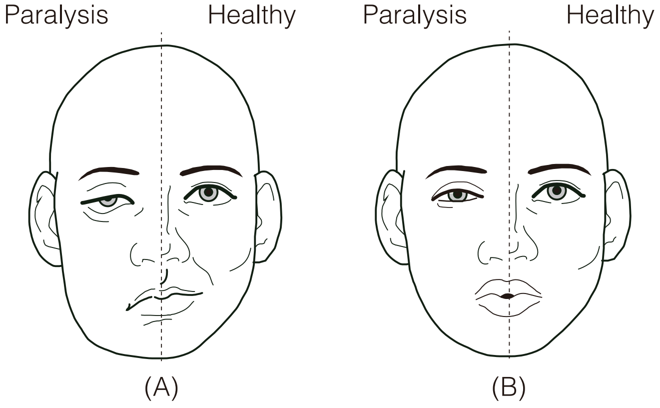

Fig. 2. Face of facial paralysis and synkinesis; (A) shows a symptom of facial paralysis. Because of the paralysis, patient loses tension of facial muscle, and face on paralysis side gets down. (B) shows a symptom of synkinesis; secondary effect of facial paralysis. The orbicularis oculi on the affected side contracting involuntary when pursing lip.

happens all day long. As eyes are one of the most sensitive body parts, it is necessary for the eyelid manipulation mechanism to be gentle and safe.

The developed wearable robot, as shown in Figure 1, supports eye opening and closure movement based on eye closure of the healthy side. For the gentle manipulation of the eyelid, an eyelid gating mechanism (ELGM) was used, which was made of soft material deformation tailored to eyelid movement. In the following section, the design requirements for eyelid manipulation are introduced. Then, the approach for the requirements are introduced. In Section IV, the development of the eyewear robot is presented. In Section V, the experiment conducted to demonstrate the characteristics of the system is discussed. Conclusion and future work are presented in Section VI.

II. DESIGN REQUIREMENT

A. The Risks and Countermeasure for Facial Paralysis

In this section, the characteristics of facial paralysis. Facial muscles serve the function of facial expression and eyelid movement. After facial paralysis, a person loses ability to use and control these facial muscles as shown in Figure 4-(A). Facial paralysis rates are reported overall 4/10,000 annum, and approximately 80% of the cases are Bell's palsy [9]. Facial paralysis could occur on both sides of face, but hemifacial paralysis is the most common with only 0.7% - 3.3% of the Bell's palsy patients having bilateral paralysis [4]. Although 80% of Bell's palsy cases are known to recover within three months, remaining 20% of facial paralysis patients suffer from severe distractions in many ways; inability to blink, make facial expressions, and purse the lips [10], and these persons need treatment for recovering. Especially, the inability to blink presents problems such as corneal dryness which can lead to corneal perforation and ultimately blindness in the affected eye if left untreated.

Moreover, facial paralysis patients need to be careful for the Synkinesis as after-effect of facial paralysis, which causes involuntary muscular movements accompanying voluntary movements as shown in Figure 4-(B). For example, the voluntary smiling will induce involuntary contraction of eye muscles [11]. Such an inappropriate wiring of facial nerves often occurs during the recovery phase. Although 80% of facial paralysis cases are known to recover within three months [10], all patients with severe facial paralysis have possibility to get synkinesis [12]. In terms of the synkinesis, once patient gets synkinesis, there is no method to cure it completely. so it is very important to prevent developing synkinesis.

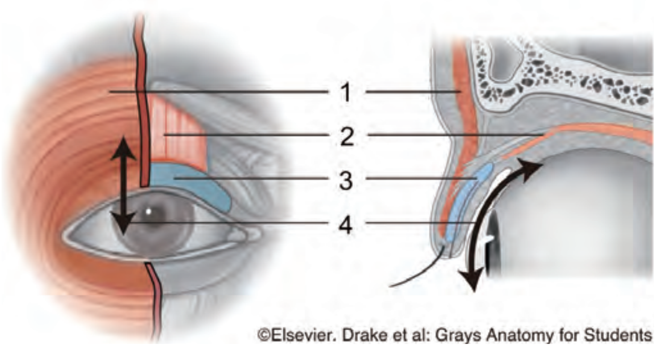

Fig. 3. Eyelid Structure. 1. Orbicularis oculi (sphincter muscle); closes eyelids. 2. Levator muscle of the upper eyelid; opens eyelids. 3. Tarsal plate (connective tissue); contributes to eyelid form and support. 4. Position of tarsal plate; set as a requirement for eyelid manipulation.

The causes of synkinesis is gross exercise on the face. Usually the patients with facial paralysis try to do rough and strong movements on the face not only paralyzed side, but also healthy side. Face on paralyzed side dose not move, but they try to move healthy side roughly and strongly to move paralyzed side. This kind of strong and rough movement promotes facial nerve recovery roughly and triggers the synkinesis. In addition, this is the reason why the appearance of the face changes greatly. physical therapists for facial paralysis instruct them try to relax facial muscle. From this, we hypothesized that if the robot assists facial movement and gave proper appropriate motion feedback, the patient can relax their facial muscle.

B. Structure of the Eyelid

In this section, the physiological characteristics of eye opening and closure movements are considered. Human beings blink all day long and eye blinking is a repetitive and high-speed movement. It is reported that the rate of blinking is once every 4 s [13] and its duration time is about 334 ms [14]. As shown in Figure 3 [15], this movement mainly uses the orbicularis oculi and the levator muscle of the upper eyelid, and these muscles manipulate the tarsal plate. The tarsal plate is a dense connective tissue, and it supports the eyelid form as a frame. The eyelid can open and close by the movement of the tarsal plate. The orbicularis oculi is a sphincter muscle that closes the eyelid when it contracts. The contraction of the levator muscle of the upper eyelid raises the tarsal plate along the spherical surface of the eyeball. Consequently, the positioning movement of the tarsal plate is three-dimensional. The movement is up and down from the front view, and in a circular arc from the side view. Therefore, a novel support method, which is gentle, three-dimensional, responsive, and robust against repetitive and high-speed movement is required to realize the support.

C. *Support Going Along with Daily Life*

In this section, the design requirement to realize continuous support going along with daily life. For the continuous usage, user cares not only function but also the experience gained from usage. According to D. A. Norman [16], human beings proceed perceived event through three cognitive levels; Visceral Behavioral and Reflective. The visceral level is fast and it makes rapid judgement of what is good or bad, safe of dangerous and so on. The behavioral level site of most human behavior. The highest layer is that of reflective thought. From them, even if the eyelid manipulation function is good enough to support, if bad impression are accumulated by continuous use, it will not lead to long-term use. Also the head is where many sensory organs gather, and it easy to make a wearer annoyed with a small amount of stress. From these, it is needed to invent the robot which can provide less stress design focusing on not only way of eyelid manipulation but also how the wearer feel while wearing this robot.

There is one approach to support facial movement with wearable robotics techniques. Dushyantha et al. [3] proposed a method to pull facial skin with shape memory alloy, and that method is called silent actuation. They mentioned that quietness is important to provide support in line with everyday life. Based on this, quietness is also a requirement for support in this study.

For eyelid movement support, Eyes are very delicate parts of the human body, not only physically delicate but also physiologically delicate. Based on this, The parts that act on the eyelids should have a replaceable or washable design. For the weight of device, lighter weight is preferable.

III. METHODOLOGY

Based on these requirements, I propose a novel robotic system for facial paralysis as shown in Figure1. As mentioned above, this system support eyelid movement on paralyzed side going along with eye blink movement on healthy side. To achieve this condition, this system can be divided into three elements; eyelid gating mechanism (ELGM), Eyelid movement sensor and eyeglass type frame. The following sections describe each element.

A. *Eyelid Gating Mechanism*

Based on the requirements for eyelid manipulation, we propose a novel mechanism made of soft material. The mechanism transforms simple inputs such as rotational actuation to three-dimensional and complex motion by deformation of the soft material. This mechanism can use rigid actuators such as a rotational motor as power source, and can thus provide responsive and robust movement. Moreover, as it is made of soft material, the mechanism can provide good affinity and does not cause overload or strain on the eye. We propose to use this novel soft robotics technology for application on the eyelid, and this is the ELGM. Several ELGM designs have been explored, such as U-shape or arc shape [17].

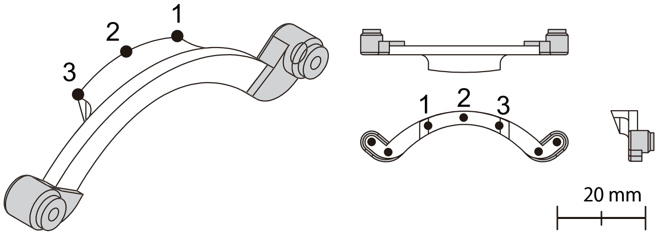

Fig. 4. Eyelid gating mechanism; the white parts are made of soft material, and the gray parts are made of rigid material. The dots show the points measured in the 3D measurement. Numbers 1, 2, and 3 are the positions that contact the eyelid.

In this study, a novel shape design of ELGM is presented, shown in Figure 4. The mechanism is a W-shaped beam fixed at two hinged ends. The axes of these hinged ends intersect in 50 deg, and they are located at the tail and inner corner of the eye. This mechanism was designed in SolidWorks and printed using Vero Clear (rigid material) and Tango Plus (soft material) by an Objet500 Connex2 3D printer (Stratasys Ltd.) in one single piece. Owing to 3D printing, it is possible to create components with various material properties from flexible to rigid, in a relatively short amount of time, and the proposed mechanism is composed of such soft and hard material composition.

B. *Eyeglasses Shape Frame*

The hinged ends on the ELGM were required to be located in the tail and inner corner of the eye. In order to achieve this requirement, an eyeglass-type frame was designed with a facial surface. First, the facial surface was scanned by a 3D scanner (Artec 3D M) and these data were exported to SolidWorks. With the scanned facial surface, the tail and inner corner was related to the back of the nose where the nose pads of the exoskeleton were located, and the eyeglass-type exoskeleton was designed with SolidWorks. This frame was printed by 3D printer using Velo Clear (rigid material) and Tango Black Plus (soft material), similar to that of the ELGM. At the hinges of the frame, Tango Black Plus (soft material) was used to adjust and fix the robot on the head of the user. Owing to this precise design with scanned facial surface and the flexibility of the ELGM, the mechanism could be fixed on the eyelid without any tape or glue owing solely to the effect of friction. As a result, a very short time is required to put on the robot (about 6 s), and the wearer can also remove the robot immediately, anytime. Owing to this feature, the robot can ensure safety.

C. *Eyelid Closure Detector*

As blinking movement is typically symmetrical, it was considered whether the healthy eye closure may serve as an appropriate trigger for eyelid movement support on the paralyzed side. Thus, we decided to detect eye closure on the

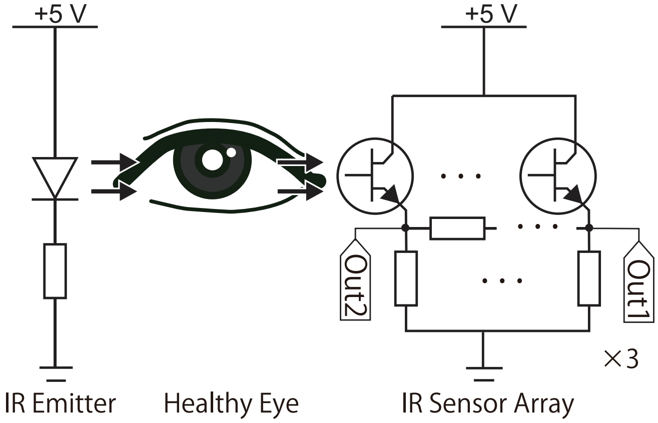

Fig. 5. Eyelid movement sensor. This sensor is composed of an emitter and a sensor array. The emitter is located at inner corner of the eye, and the sensor array is located at tail corner of the eye. The sensor arrays are arranged side by side in the vertical direction.

healthy side as a trigger for the support. There are three types of eye blink: spontaneous blink, reflex blink, and voluntary blink. Spontaneous blink is what we perform in everyday life without conscious efforts, like breathing and digestion. Reflex blink occurs in response to an external stimulus. Suppressing the onset of synkinesis, it is important to relax the facial muscles as much as possible and not put strong forces on the face. From this, it is ideal to detect spontaneous blink as a trigger for eyelid movement support.

Although many closure detection methods have been studied so far[18][19][20], there are few sensors that can detect spontaneous blink robustly. On the contrary, A. Frigerio et al. proposed a method to detect spontaneous blink applying photo interrupter approach. They implemented an eyeglass locating IR emitter at inner corner of the eye, and photo transistor at tail corner of the eye. Once wearer blinks, the eyelid movement can be detected by blocking the infrared light from the emitter with the eyelid. In their case, they just implemented only one photo transistor and it is possible to distinguish if eyelid is open or close, and because of this, it was difficult to distinguish eyelid closure and saccade from center to downward.

Based on this approach, I developed an array of photo transistors and examined a new method for distinguishing between eyelid closure and saccade movement. In designing the transistor array, I referred to researches done by S. Makoto et al.[21][22]. They proposed a net-structure proximity sensor, and it can calculate two dimensional position information from four voltage outputs. In my case, I build three sensor lines in horizontal direction to get vertical movement of eyelid, as shown in Figure 5. Thanks to array structure, the position of eyelid can be obtained with higher resolution than mono transistor method, and the difference between the saccade and eye blink movement signal could be high enough to distinguish them. Figure 6 shows the signals obtained from the sensor when the wearer is blinking at a certain cycle. (A) indicates row signal, and (B) indicates differentiated signal, and its window size was 10ms. The difference of the color is the position of sensor array. As you see these figure, this sensor can obtain robust signal of eyelid movement while maintaining the advantages of Infrared sensor as a safe, non contact, invisible and inexpensive reporter of blink occurrence and duration.

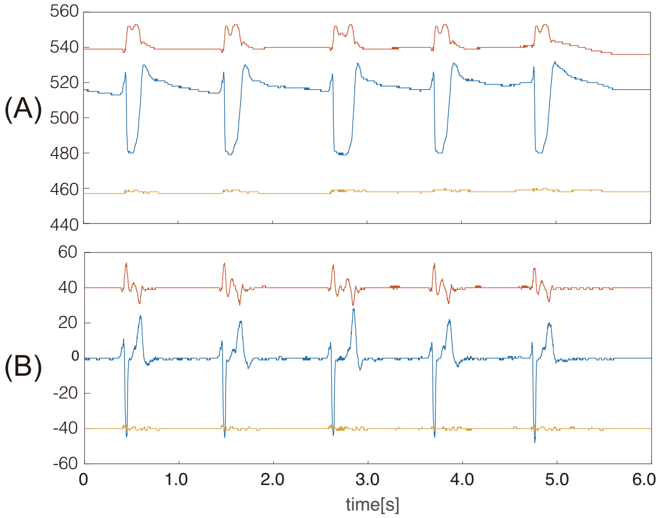

Fig. 6. Obtained signal from an eyelid closure sensor. Data was acquired at a sampling rate of 1kHz. Upper graph shows row signal from sensor and bottom one is differentiated signal, and its window size is 10 ms. Each color shows the position of sensor, and red is front, blue is middle, yellow is back.

D. *Eyewear Robot for Supporting Eyelid Closure*

With these elements, we have made a prototype of eyewear robot as shown in Figure 7. This prototype was composed of a battery, a controller, a sensor, an actuator, and the ELGM. These parts were installed on an eyeglass-type exoskeleton frame. Its dimensions were 155 × 205 × 25 mm, and weight was 90.1 g. A servo motor was used in this robot and its rotational power was transmitted to the ELGM via a pulley-wire system. The diameter of the pulley on the ELGM was 7 mm and the diameter of the servo motor was 8 mm. The material of the wire was stainless steel and its diameter was 0.45 mm. A copper cylinder was used as a wire guide. The controller part used an Arduino Microcontroller.

IV. EVALUATION

Here an experiment was conducted to evaluate the developed system. As mentioned above, the blinking movement is typically symmetrical. Because of this, the closure of the healthy eye may serve as an appropriate trigger for eyelid movement support on the paralyzed side. To fulfill this requirement, the robot is expected to support eyelid closure based on eye closure on the healthy side. To evaluate this system, the change in the degree of eye opening with respect to time was measured. In this evaluation, voluntary eye closure was detected as a trigger for support.

A. *Experimental Conditions*

A healthy subject participated in the experiment. He wore the robot and his head was fixed on a chin stand. He

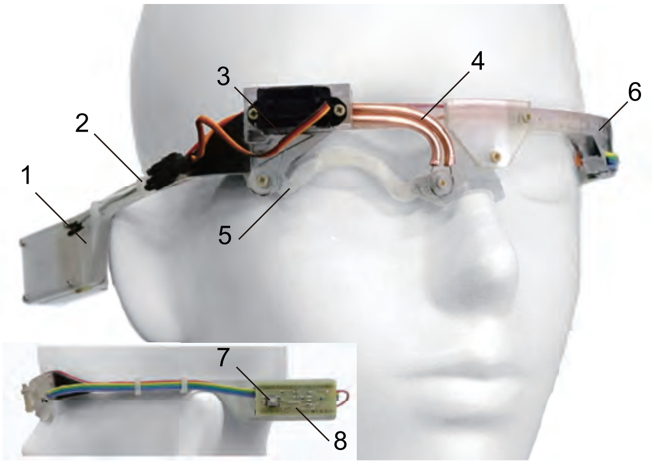

Fig. 7. Eyewear robot. 1. Battery. 2. Eyeglass-type exoskeleton; designed with facial surface scanned by 3D scanner. 3. Servo motor. 4. Pulley mechanism: transmits rotational power to eyelid gating mechanism from servo motor. 5. Eyelid gating mechanism: deformation tailored to the movement of the eyelid. 6. Reflective optical sensor: detects voluntary eye closure on the healthy side. 7. Button for the calibration of eye closure detection. 8. Controller.

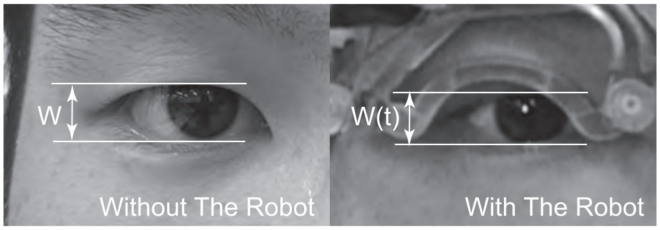

Fig. 8. Measurement range for Palpebral aperture ratio, $W(t)$ is a variable value and it is operated by the robot, W is constant value with respect to time.

calibrated the threshold for eye closure detection. Following calibration, he was asked to close his eye on the left side and make the robot support his eye on the right side. This movement was tracked by using a camera with a frame rate of 60 fps. The same procedure was repeated for five sessions. Following all sessions, the participant removed the robot. Images were taken of the participant with open eyes without the robot to compare the eye area with and without the mechanism.

To determine the changes of the degree of eye opening with respect to time, the ratio of the width of upper and bottom eyelids was calculated with (variable) and without the robot (constant); this ratio is called palpebral aperture ratio (PAR). PAR is described as follows:

$$PAR(t) = \frac{W(t)}{W} \times 100, \quad (1)$$

where W is the width without the robot and it is constant, $W(t)$ is the width with the robot and it is time-dependent. As shown in Figure 8, these widths of the upper and bottom eyelids were measured manually from the obtained images, and the ratios were calculated for each frame.

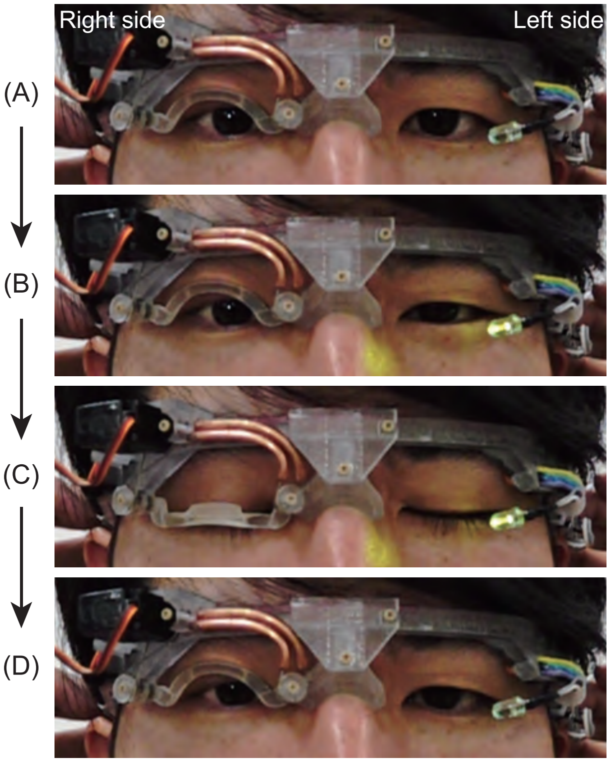

Fig. 9. Demonstration of the robot presented. A camera was used with a rate of 60 fps, to extract the pictures. (A) Initial state. (B) Detection of voluntary eye closure on the left side and green LED is an indicator of detection. (C) Closure actuation of the mechanism. (D) Opening actuation of the mechanism.

B. Results

The results of this experiment are shown in Figures 9, 10, and 11. Figure 9 shows a snapshot series of the function of the system. Picture (A) shows the initial state, (B) shows the detection state, (C) shows the closure actuation state, and (D) shows the opening actuation state. Figure 10 shows the change of PAR with respect to time. As mentioned above, the procedure was measured five times, and Figure 10 is the first result of the five measurements. The red line shows the change of PAR on the left side and the blue line shows the change of PAR on the right side. The green line shows the time when voluntary eye closure was detected as well. This shows the average of PAR when voluntary eye closure was detected, which was 90.6 ± 1.58 %. Moreover, the average value of "A" was calculated and shown in Figure 10. Value "A" shows the delay between the eye closure on the left side and the right side, and its value was 100.0 ± 10.5 ms. The time taken to support eye opening and closure movement was also calculated, which was 556.7 ± 13.5 ms. The onset of eye closure and the termination of eye opening are defined as the point where PAR is 95 %. These values are shown in Figure 11.

V. DISCUSSION AND CONCLUSIONS

These results suggest that the proposed robot can support eye opening and closure movements based on voluntary eye

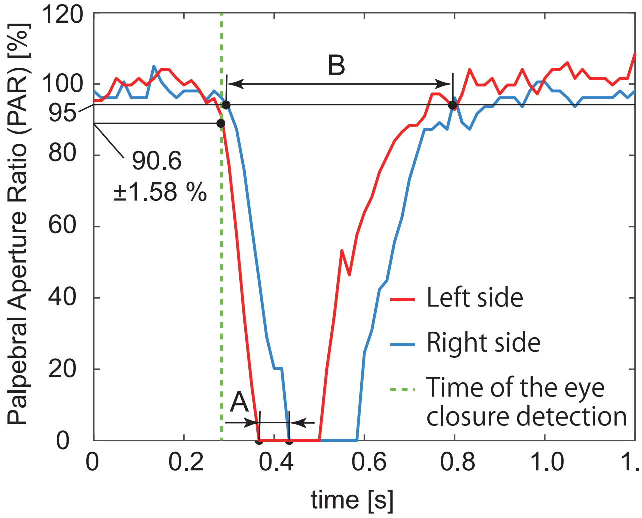

Fig. 10. Result of change of palpebral aperture ratio (PAR) with respect to time. The red line shows the change of PAR on the left side, the blue line shows the change of PAR on the right side, and the green line shows the time when voluntary eye closure is detected. "A" is the time lag between eye closure on the left side and the right side, and "B" is the PAR when voluntary eye closure is detected.

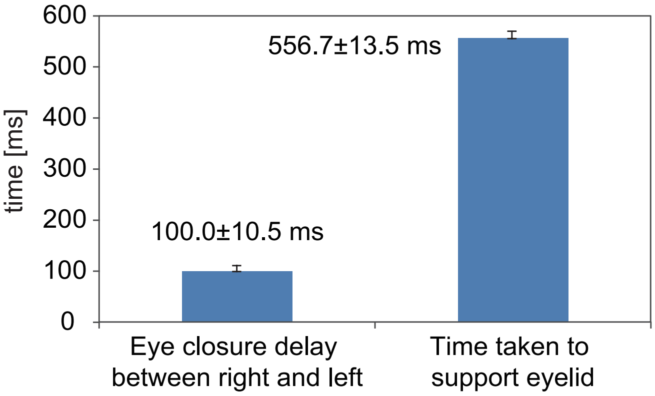

Fig. 11. Obtained experimental values. "Eyelid closure delay between right and left" shows the average value of "A" in Figure 10. "The time taken to support eyelid" shows the average value of "B" in Figure 10.

closure on the other face side, and its time lag is about 100 ms. Thus, a novel sphincter muscle support method can be realized, and it can be shown that it is possible to achieve support of repetitive and gentle eyelid movements based on the intention of the wearer. Based on this, the robot might become a viable rehabilitation equipment for facial paralysis. As mentioned above, synkinesis often occurs during the recovery phase, and care must be taken to prevent its development. The developed robot can help with biofeedback enabled rehabilitation, and thus, it can be useful to correct eyelid movement, and contribute to rehabilitation against synkinesis.

In this paper, we proposed a novel approach for supporting eye opening and closure movements by an eyewear robot. The robot has a novel ELGM, using deformation of soft material to move the eyelid. The requirements for the movements of the eyelid were set, and the deformations of the mechanism were designed accordingly. As a result, deformation can be controlled tailored to the eyelid movements by simple rotational inputs at the two hinged ends of the ELGM. This system provides appropriate support for eye opening and closure in a non-invasive and gentle manner, based on voluntary eye closure on the healthy side. The system was evaluated with a healthy participant and indicated the feasibility of eye opening and closure support by the developed system.

In the future, we plan to develop this wearable robot as a rehabilitation equipment for facial paralysis. The developed robot may support rehabilitation to recover the paralysis faster and to prevent the development of after effects such as synkinesis.

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