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# Development of a Smart Assistance System for Patients With Blepharoptosis

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**ABSTRACT** Blepharoptosis is defined as an abnormal low-lying upper eyelid margin in primary gaze. Without adequate management, the disease may cause amblyopia, strabismus, and astigmatism in children as well as constriction of the upper visual field, blurred vision, increased tearing, fatigue, and frontal headache in adults. In most cases of blepharoptosis, surgical intervention is the primary treatment. However, the risk of recurrence is high, and some complications may occur after the surgical intervention. Although ptosis crutches and magnetic eyelid devices have been reported to be beneficial for managing the disease, many disadvantages must be overcome. To avoid sequelae from the disease and to mitigate the discomfort and complications, this study proposes a novel assistance system. In this system, a controllable permanent electromagnet and a piece of iron sheet affixed to the paralytic upper eyelid were used for elevating the drooping eyelid according to the degree of the eyelid being opened or closed, as estimated by an optical probe. Finally, the performance of the proposed system in detecting eyelid actions and the effect of eyelid elevation were validated. The experimental results showed that the proposed system could effectively detect eyelid closing events and successfully, symmetrically, and synchronously elevate the drooping upper eyelid with a mean correction of  $3.5 \pm 0.4$  mm (range, 2.7 – 4.0 mm) in 14 patients with unilateral blepharoptosis. The proposed system therefore may be applied to patients with unilateral blepharoptosis in the future.

**INDEX TERMS** Blepharoptosis, blink detection, eyelid elevation, magnetic device, ptosis, wearable assistance system.

## I. INTRODUCTION

Blepharoptosis is an abnormal low-lying upper eyelid margin in primary gaze and results in narrowing of the palpebral fissure opening [1]. The prevalence of blepharoptosis in Korea and the United Kingdom has been reported to be approximately 11% [2], [3]. Unilateral blepharoptosis is defined as either a measured palpebral fissure asymmetry of  $\geq 1$  mm between the two upper eyelids or a marginal reflex distance of  $< 2.5$  mm [4]. According to the gap in the palpebral fissure, the degree of severity can be classified as minimal (1–2 mm), moderate (3–4 mm), or severe ( $> 4$  mm). Without adequate management, morbidities from blepharoptosis, namely,

constriction of the upper visual field, blurred vision, increased tearing, and a sleepy appearance, can occur [5]. For most cases of blepharoptosis, surgical intervention is the primary treatment [5]. However, there is a high reoperation rate (3%–72%), and complications following the surgical intervention may occur [5]–[7].

Ptosis crutches have been reported to be an alternative nonsurgical treatment for blepharoptosis [8]. Because conventional ptosis crutches have disadvantages, such as interference with blinking, dry eye, and frequent eye irritation, they are not widely used [9]. The magnetic levator prosthesis has also been used for the temporary management of blepharoptosis [10], [11]. To overcome the magnetic force between the magnets affixed to the upper eyelid and the magnet mounted on glasses, considerable effort is required to close the upper

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eyelid, which can cause upper eyelid discomfort and erythema [11].

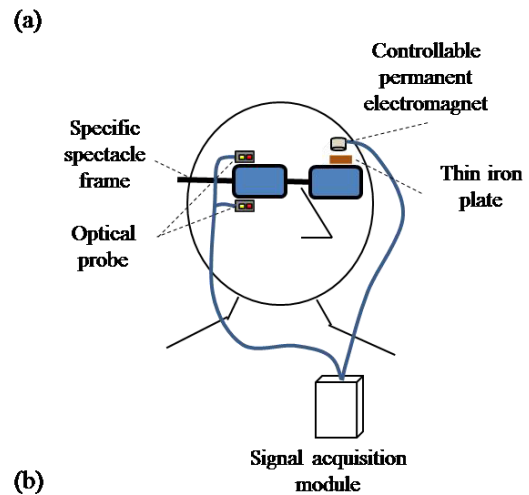
To mitigate the discomfort and complications, a novel assistance system was designed and implemented to assist in restoring the symmetric and synchronous elevation of the paralytic upper eyelid for patients with unilateral blepharoptosis in the present study. In this system, optical probes were used for monitoring the eyelid closing events, and a controllable permanent electromagnet and a piece of iron sheet were used for elevating the drooping eyelid. When the closing of an eyelid was detected, the controllable permanent electromagnet was disabled to release the drooping eyelid. In contrast to conventional surgeries, ptosis crutches, and magnetic eyelid devices, the proposed system did not introduce a risk for discomfort or complications. Finally, the performance of the proposed system in detecting eyelid actions was validated, and the effect of the eyelid elevation and responses to a satisfaction questionnaire were also evaluated. From the experimental results, it was determined that the proposed system could effectively assist patients in achieving symmetric and synchronous elevation of a paralytic upper eyelid and might be applied to patients with unilateral blepharoptosis in the future.

## II. METHODS AND MATERIALS

### A. DESIGN AND IMPLEMENTATION OF THE ASSISTANCE SYSTEM FOR OPENING EYES

The basic scheme and a photograph of the proposed system are presented in Fig. 1 (a) and Fig. 1 (b). The system primarily consisted of the following parts, including a specific spectacle frame, a controllable permanent electromagnet, a thin iron plate, an optical probe, and a signal acquisition module. The controllable permanent electromagnet was placed on the specific spectacle frame, and the thin iron plate was placed on the upper eyelid of the unilateral paralytic eye. The optical probe was also placed on the spectacle frame to detect eyelid closing or opening events on the basis of the variation in the reflected light rays when the state of the eyelid changed. The signal acquisition module was designed to drive and control the permanent electromagnet as well as drive and receive information from the optical probe to determine the activity of the eyes. The controllable permanent electromagnet initially generated an external magnetic field, and the thin iron plate was attracted by the external magnetic field to assist in opening the eyelid. When the closing of an eyelid was detected, the signal acquisition module drove the controllable permanent electromagnet to neutralize the external magnetic field and thereby assisted in closing the eyelid.

The size of the spectacle frame employed in the study was approximately 136 mm × 134 mm × 33 mm. There were two adjustable acrylic brackets on the spectacle frame. One bracket was designed to fix the controllable permanent electromagnet near the upper eyelid of the unilateral paralytic eye, and the other bracket was designed to fix the optical probes near the eyelid of the normal eye. The structures of these adjustable acrylic brackets mainly consisted of three



**FIGURE 1.** (a) Basic scheme and (b) photograph of proposed assistance system for opening eyes.

components, including a telescopic body, a supporting pedestal, and a placement platform. These brackets could be mounted on the spectacle frame using the supporting pedestal. The telescopic body was used for adjusting the distance and angle between the supporting pedestal and the placement platform. The controllable permanent electromagnet and the optical probes could be placed on the placement platform.

The designed optical probe contained two pairs of light sources and detectors. The probe mainly consisted of tri-wavelength light emitting diodes (LEDs; SMT640/700/910, EPITEX, Japan) and a photodiode (PD; PD15-22C/TR8, EVERLIGHT, Taiwan) to provide a light source and receive the reflected light from the skin. The flash frequency of the LEDs is approximately 50 Hz, and its maximum power is approximately 15  $\mu$ W, satisfying the safety criterion of a human experiment [12]. In addition, an acrylic baffle is also affixed below the LEDs to prevent the light from injuring the eyes. Here, the distance between the light source and the PD was approximately 6 mm.

The controllable permanent electromagnet (JNF-12/12K-DC12V, Shenzhen Join Magnetic Co., Ltd, China) contained a constant permanent magnetic field that could be neutralized when a specific voltage was applied to it. The

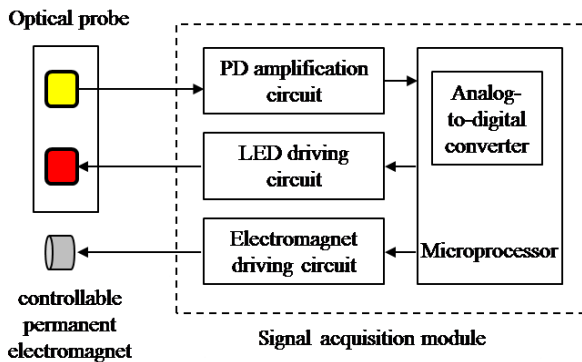


FIGURE 2. Block diagram of the signal acquisition module.

size of the controllable permanent electromagnet used in the system was approximately  $1.2 \text{ cm} \times 1.2 \text{ cm}$ . Moreover, it could provide a magnet suction strength between 10 N and 0.2 N when a voltage between 0 V and 12 V was applied.

The block diagram of the signal acquisition module, Fig. 2, mainly consisted of an electromagnet driving circuit, a PD amplification circuit, an LED driving circuit, and a microprocessor. The LED driving circuit was designed to drive the LEDs and thus provide a steady light source. The electromagnet driving circuit was designed to provide a constant current to the controllable permanent electromagnet. Both the LED driving circuit and electromagnet driving circuit could be turned on and off by the microprocessor (RX210, Renesas, Japan). The design of the PD amplification circuit was based on a trans-impedance amplifier. The photocurrent of the reflected light signal received by the PD was converted and amplified to a voltage signal by the PD amplification circuit. Experimentally, it was determined that the gain of the PD amplification circuit was approximately 240. Next, the reflected light signal was digitized by a 12-bit analog-to-digital converter built in the microprocessor with a sampling rate of 50 Hz, and then the signal was processed by the proposed algorithm to detect eyelid closing and opening events. When an eyelid closing event was detected, the microprocessor controlled the electromagnet driving circuit to enable the controllable permanent electromagnet and assisted in closing the eyelid.

### B. EYELID CLOSING DETECTION ALGORITHM

In the act of blinking, the reciprocal relationship between innervation patterns of the levator palpebrae superioris and orbicularis oculi muscles causes the simultaneous movements of the upper and lower eyelids [13], [14]. However, some facial movements, such as raising the eyebrows, frowning, and smiling, also cause movements of the upper or lower eyelids [15]. To improve the accuracy of eyelid blink detection and reduce the influence of other facial movements, two pairs of light sources and detectors were embedded into the optical probe to monitor the movements of the upper and lower eyelids simultaneously. The movements of the upper and lower eyelids could be detected from the change in the

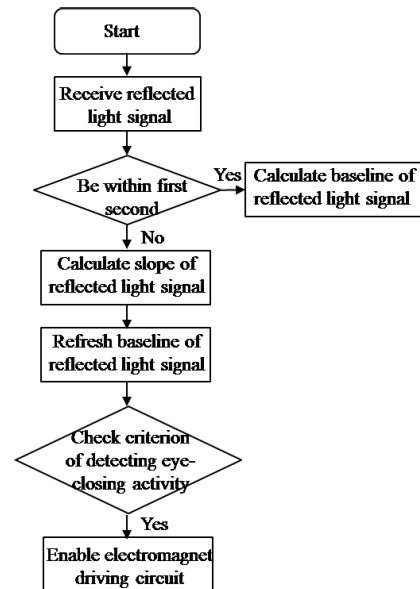


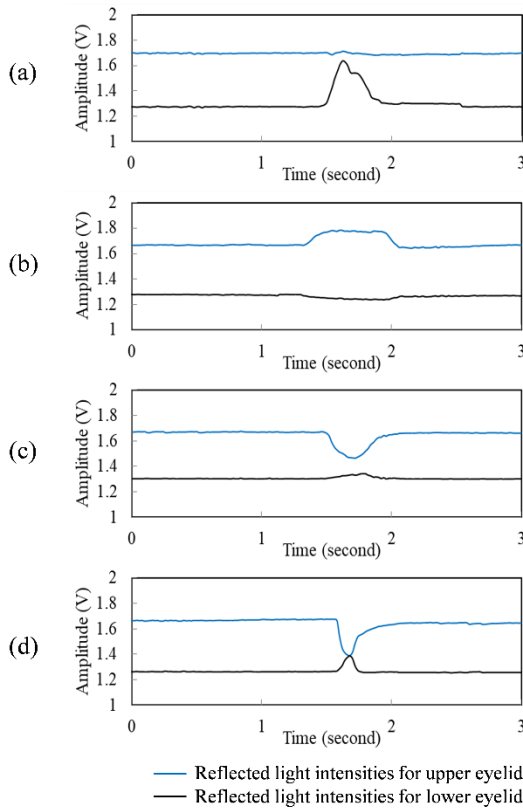
FIGURE 3. Procedure of the eye-closure- detection algorithm.

optical density of the reflected light caused by a change in the light rays between the light source and the eyelids. When the eyes closed, the distance between the light source and the upper and lower eyelids became longer and shorter, causing a decrease and an increase in the optical densities, respectively.

The proposed algorithmic procedure for eyelid closure detection is illustrated in Fig. 3. In the beginning, the user was instructed to look straight ahead and hold the head steady for approximately 3 s. The average of the first and second reflected light signals received from the upper and lower light detectors was calculated and used as baselines. Afterwards, the algorithm was used for calculating the slope of the reflected light signals by using the first derivative approach [16] to estimate the variation in the optical densities. Let  $x(k)$  denote the reflected light signal at iteration  $k$ , and then its slope  $y(k)$  at iteration  $k$  could be calculated by

$$y(k) = \sum_{l=-\frac{w}{2}}^{l=\frac{w}{2}} l \cdot x(k+l) \quad (1)$$

where  $w$  was the sliding- window length, which was set to 0.1 s in this study. When the slope value changed from positive/negative to negative/positive, the reflected light signal contained a local maximum/minimum value. If the local maximum/minimum was higher/lower than the baseline, an event mark was created. If the duration between the two nearest event marks obtained from the upper and lower eyelids was within 0.2 s [17], this period of time was considered an instance of eyelid closure. Moreover, the baseline of the reflected light signal was also updated by the dynamic moving average method [18]. With the dynamic adjustments of the baseline, the influence of the light- signal variation across subjects or across sessions could be effectively reduced. Finally, the electromagnet driving circuit was enabled upon the occurrence of eyelid closure.



**FIGURE 4.** Changes in the reflected light intensities when the user is (a) smiling, (b) frowning, (c) raising the eyebrows, and (d) blinking.

**III. RESULTS**

**A. EFFECT OF EYELID MOVEMENTS ON THE REFLECTED LIGHT INTENSITY**

This section presents the results of the effect of eyelid and facial movements on the change in reflected light intensity. Fig. 4 (a)–(d) presents the change in the reflected light intensities under various eyelid and facial movements, including smiling, frowning, raising the eyebrows, and blinking. The blue line and black line represent the reflected light signals obtained from the upper and lower eyelids, respectively. When smiling occurred, the skin near the lower eyelids moved close to the optical probe, causing a peak in the black line but no apparent change in the blue line. In contrast to smiling, frowning caused the skin near the upper eyelids to move near to the optical probe, causing a peak in the blue line but no apparent change in the black line. When the eyebrows were raised and blinking occurred, the skin near the upper eyelids moved far away from the optical probe, causing a trough in the blue line; however, the skin near the lower eyelids moved close to the optical probe, causing a peak in the black line. Compared with raising eyebrows, blinking caused the skin near the lower eyelids to move closer to the optical probe and caused a higher peak in the black line.

**B. PERFORMANCE OF THE PROPOSED SYSTEM FOR DETECTING EYELID CLOSING EVENTS**

This section discusses the investigation results of the performance of the proposed system for detecting eyelid closing

when the user is sitting, walking, or engaging in various facial movements. Ten individuals participated in this experiment. The participants were instructed to sit on a chair, walk in the same place, and change their facial expression (e.g., smile, frown, raise their eyebrows, and blink voluntarily). A webcam was placed 2 m in front of the participant to record the true eyelid blinking occurrences for 3 minutes. Finally, the eyelid closing events were estimated using the proposed algorithm and compared with the true eyelid closing occurrences recorded by the webcam. To evaluate the performance of the eyelid closing detection algorithm, several parameters for the classification test had to first be defined. Here, a true positive (TP) result denoted that the eyelid closing event was correctly recognized as an eyelid closing event. A false positive (FP) result denoted the false detection of an eyelid closing event. A true negative (TN) result denoted the correct recognition of the absence of an eyelid closing event. A false negative (FN) result denoted that an eyelid closing event was not recognized. Here, the value of the F-measure [19], [20] was used for evaluating the performance of the eyelid closing detection algorithm, and it was calculated by

$$F\text{-measure} = 2 \times \frac{\text{precision} \times \text{recall}}{\text{precision} + \text{recall}} \tag{2}$$

where precision and recall denoted positive predictive value (PPV) and sensitivity respectively, which were calculated by

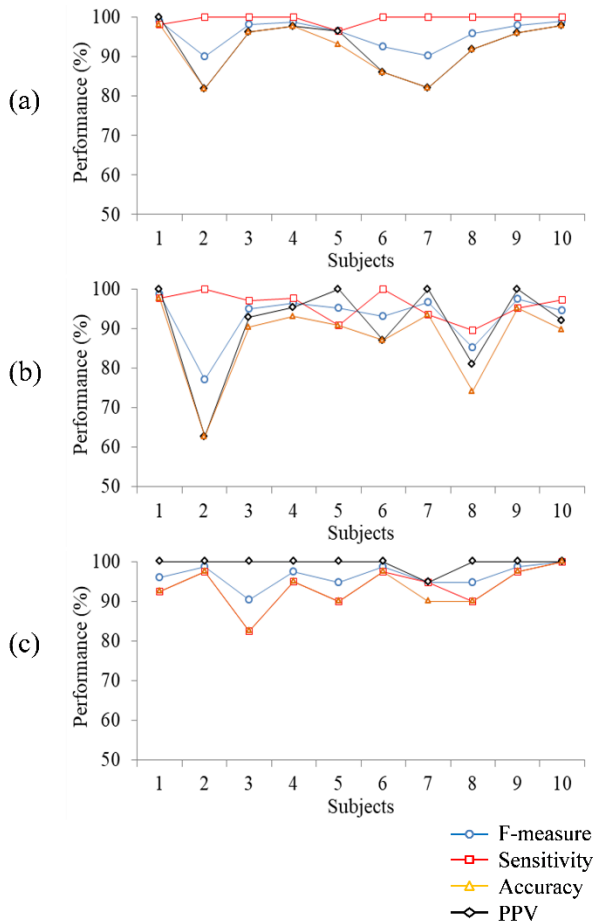
$$\text{precision} = \frac{TP}{TP + FP} \times 100\% \tag{3}$$

$$\text{recall} = \frac{TP}{TP + FN} \times 100\% \tag{4}$$

Fig. 5 (a), Fig. 5 (b), and Fig. 5 (c) depict the values of F-measure, sensitivity, PPV, and accuracy of the proposed system in detecting eyelid closing events when sitting, moving, and engaging in various facial movements, respectively. The average F-measure, sensitivity, PPV, and accuracy of the proposed system under the conditions of sitting, walking, and engaging in various facial movements were (95.8%, 99.4%, 92.6%, 92.1%), (92.9%, 95.9%, 91.1%, 87.4%), and (96.4%, 93.7%, 99.4%, 93.25%), respectively.

**C. PERFORMANCE IN A CLINICAL EXPERIMENT**

This section discusses the performance of the proposed system assisting patients with blepharoptosis in elevating their paralytic upper eyelids. Fourteen patients with unilateral blepharoptosis participated in the clinical experiment. The clinical experiment was performed at E-DA Hospital after obtaining Institutional Review Board approval from E-DA Hospital and the Taiwan Food and Drug Administration (IRB approval number: EMRP33106N; IRB date: August 23, 2018). All patients provided written informed consent for this experiment. Before the experiment, an iron sheet was affixed to the paralytic upper eyelid with double-sided adhesive tape and Miropore tape. The controllable permanent electromagnet was partially wrapped in an insulated sponge (Scotch, 3M



**FIGURE 5.** Performance of the proposed system for detecting eyelid closing when the user is (a) sitting (b) walking, and (c) engaging in various facial movements.

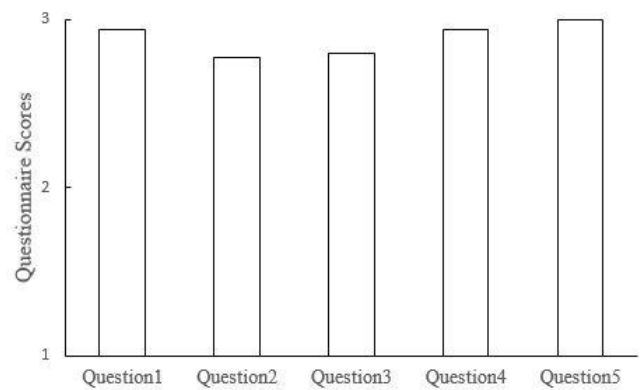
Corporation, USA) to prevent the surface from overheating, which might cause damage to the skin.

During the experiment, patients were instructed to sit on a chair and open their eyes naturally. A ruler and a webcam were fixed in front of the participant to record the interpalpebral fissure length (IPFL) before and after the use of the proposed system. Here, IPFL was defined as the greatest distance between the upper and lower eyelid margins at the base of the eyelid lashes [21], [22]. The degree to which IPFL improved was analyzed using the National Eye Institute ImageJ software (ImageJ Version 1.52h, National Institutes of Health, USA). Moreover, each patient was asked to blink spontaneously for three minutes, and the webcam recorded the true eye blink instances to investigate the influence of eyelid dysfunction on the detection of eyelid closing instances.

Finally, each participant was instructed to complete a questionnaire, Table 1, to evaluate the comfort and efficacy of the proposed system. The questionnaire results are depicted in Fig. 6. According to the experiment, which involved 14 patients with unilateral blepharoptosis, the mean corrective distance (gain) was  $3.5 \pm 0.4$  mm (range, 2.7–4.0 mm). Fig. 7 displays the measured IPFL of four cases before and after using the proposed system. The four cases were selected

**TABLE 1.** Questionnaire regarding the comfort and efficacy of the proposed system.

Q1: Score the degree to which the visual axis is improved from using the proposed system. (Good: 3 points; Average: 2 points; Poor: 1 point)	<input type="checkbox"/> Good	<input type="checkbox"/> Average	<input type="checkbox"/> Poor
Q2: Score the severity of blurred vision when using the proposed system. (None: 3 points; Mild–moderate: 2 points; Severe: 1 point)	<input type="checkbox"/> None	<input type="checkbox"/> Mild–moderate	<input type="checkbox"/> Severe
Q3: Score the degree of heat insulation when using the proposed system. (Good: 3 points; Average: 2 points; Poor: 1 point)	<input type="checkbox"/> Good	<input type="checkbox"/> Average	<input type="checkbox"/> Poor
Q4: Score the severity of a foreign sensation affecting the eyeball when using the proposed system. (None: 3 points; Mild–moderate: 2 points; Severe: 1 point)	<input type="checkbox"/> None	<input type="checkbox"/> Mild–moderate	<input type="checkbox"/> Severe
Q5: Score the severity of eyelid erythema and swelling when using the proposed system. (None: 3 points; Mild–moderate: 2 points; Severe: 1 point)	<input type="checkbox"/> None	<input type="checkbox"/> Mild–moderate	<input type="checkbox"/> Severe

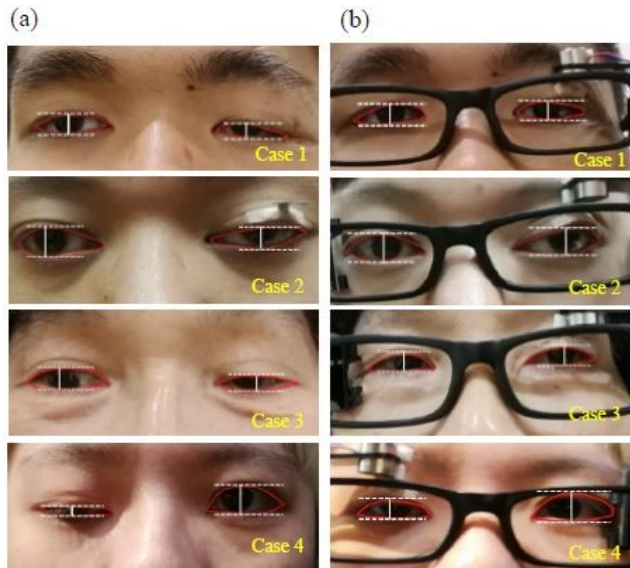


**FIGURE 6.** Questionnaire results regarding the comfort and efficacy of the proposed system.

at random. The white dashed line, red line, and white line represented the position of greatest eyelid separation, the eyelid margins, and IPFL, respectively. The IPFLs of the right and left eye reported as (right IPFL, left IPFL) for case 1, case 2, case 3, and case 4 before using the proposed system were (10.5 mm, 5.7 mm), (11.7 mm, 6 mm), (10.2 mm, 7.1 mm), and (3.2 mm, 12 mm), respectively, and their IPFLs for the right and left eyes became (10.5 mm, 9.5 mm), (11.7 mm, 9.6 mm), (10.2 mm, 10.5 mm), and (6.7 mm, 12 mm), respectively, after using the proposed system.

#### IV. DISCUSSION

In this study, the proposed system was designed to automatically assist the levator muscle function of a patient with blepharoptosis according to the state of contralateral eyelid closing or opening. From the experimental results, it was determined that the proposed system could effectively detect the state of eye closing. The accuracy of the proposed system in detecting eyelid closing events when a patient was sitting was approximately 92%, which was comparable to the accuracy obtained through the use of EMG processing,



**FIGURE 7.** Measured IPFLs of four randomly selected participants (a) before and (b) after using the proposed system.

a video camera, and IR (infrared) emission and detection (87%–95%) [23]–[25].

The system was also able to achieve a high performance level when a patient walked or engaged in facial movements; however, the shifting of the glasses because of the movement of the skin at the bridge of the nose or upper cheek [26] caused a variation in the reflected light rays between the light source and eyelids that slightly affected the performance. The performance might be improved by using an eyeglass strap or antislip nose pads to increase the stability of the spectacles on the face.

For the 14 patients with unilateral blepharoptosis, the mean gain in IPFL from using the device prototype was  $3.5 \pm 0.4$  mm, which was comparable to the results (1.0–4.0 mm) for patients treated with frontalis suspension and/or levator muscle resection [27]–[30]. Although frontalis suspension is an effective surgical method for the correction of severe ptosis, the outcome of the procedure depends on a patient having good preoperative frontalis muscle function [31]. In addition, surgical outcomes also depend on the severity of ptosis and levator function [5]. Therefore, the device might be applied to assist in managing patients with ptosis and poor levator and frontalis muscle function, which was a problem that might be caused by traumatic injury or a cerebrovascular accident (e.g., case 1 and case 4) and was difficult to treat successfully with surgical interventions.

The experimental results in Fig. 6 demonstrated that the IPFLs of the eyes were improved in all cases and restored to the normal length of 7–12 mm [32]. In case 4, the lower performance level in elevating the drooping eyelid could be explained by the physics of ferromagnetism [33] that the attraction between the thin iron plate and the controllable permanent electromagnet was diminished by an increasing distance. Although the difference in IPFLs between both

eyes of case 4 could not be improved completely to a normal value [27], the corrected distances still considerably improved the subject's visual axis obstruction and made the eyes more symmetrical.

Surgical interventions remained the primary treatment strategy. Undercorrection might cause residual ptosis, and overcorrection might cause incomplete eyelid closure (lagophthalmos). Surgeons faced the dilemma of how to avoid overcorrection and undercorrection. In this study, the average corrective distance of patients who wore the proposed device was  $3.5 \pm 0.4$  mm. All patients reported an improvement in visual axis obstruction. Both synchronous and symmetric elevation of the paralytic upper eyelid was observed. The proposed device achieved complete improvement in patients with mild-to-moderate ptosis and partial improvement in patients with severe ptosis in terms of efficacy and aesthetics.

Several treatment modalities for blepharoptosis have been proposed in other studies, including frontalis suspension surgery, levator resection surgery, ptosis crutch, and magnetic levator prosthesis. From the experimental results in 12 patients with blepharoptosis, the mean corrective gain using the magnetic levator prosthesis is excellent (approximately 9 mm) [11]. The prosthesis may cause incomplete eyelid closure during spontaneous blinking movements and some overcorrection, so the treatment effect is subjectively considered to be good. Although the mean gain using the ptosis crutch is also excellent (7 mm), due to the uncoordinated and unstable blinks and obviously incomplete eyelid closure, the treatment effect is subjectively considered to be poor. Because the mean gain using surgical interventions and using this device prototype revealed a good result and stable synchronous symmetric blinking without incomplete eyelid closure was observed, the treatment effect was considered to be good. A comparison of the proposed system and other approaches is presented in Table 2. Until now, surgical intervention has been the primary treatment for most cases of blepharoptosis [5]. However, a high rate of reoperation (3%–72%) and some complications following the surgical intervention may occur [5]–[7]. Therefore, some devices were developed to overcome this problem. In 2018, Rojdamrongratana *et al.* used 3D printing to design a new ptosis crutch prototype [33]. Their proposed ptosis crutch consisted of two adjustable clips that were connected by a supporting arch and attached to the frame of spectacles. The supporting arch was tucked in the eyelid to raise it above the pupil. By adjusting the distance between the two clips, the supporting arch can change the degree of eyelid elevation. The advantages of this design included a low manufacturing cost and adaptability of use for most patients with blepharoptosis. However, the user must frequently adjust the crutch to elevate the eyelids, which some users might find inconvenient. Moreover, overuse of the ptosis crutch could also result in complications such as ocular desiccation and incomplete eyelid closure. To overcome these problems, Houston *et al.* proposed magnetic levator prosthesis [11].

**TABLE 2.** Comparison of the proposed system with other systems or methods for the treatment of blepharoptosis.

Approaches	Surgical intervention [5]	Ptosis crutch [8], [9]	Magnetic levator prosthesis [11]	The proposed system
Treatment effect*	Good	Poor	Good	Good
Cost	High	Low	Medium	Medium
Advantages	No external devices required	No surgical complications, better adaptability of use	No surgical complications	No surgical complications, self-adjustable
Disadvantages	High reoperation rates; complications such as keratopathy, dry eyes, entropion, infection, scarring, and lagophthalmos	Interference with blinking, ocular desiccation or irrigation, incomplete eyelid closure	External device required; discomfort, erythema, or erosion of upper eyelid; magnets affixed to the upper eyelid	External device required; optical emitter and sensor, iron sheet affixed to the upper eyelid
Limitation of use	Poor frontalis muscle function and levator function, keratitis sicca	Crutch must be frequently adjusted to elevate the eyelids	Interference with static magnetic environment	Interference with static magnetic or light environments

\*According to corrective distance (interpallebral fissure), stability, and synchronous symmetric blinks (complete eyelid closure)

This device contains a magnet array and a neodymium-52 (NdFeB) axially magnetized cylinder mounted on the frame of spectacles. The magnet array consists of several rectangular NdFeB magnets embedded in a polydimethylsiloxane biocompatible elastomer that is affixed to the upper eyelid. By arranging the magnetic pole orientation between the magnet array and the cylinder, the mutual attraction between the array and cylinder elevates the eyelid. By using the mechanism of magnetism, this strategy demonstrates superior performance on eyelid elevation compared with other devices. However, because the magnetic levator prosthesis device lacks a mechanism for neutralizing the magnetic attraction, users could not close their eyes naturally and experienced discomfort, erythema, or erosion of the upper eyelid skin. In this study, the proposed system overcame these problems. In the proposed system, an optical probe was designed for detecting eyelid closing and opening events. Moreover, a controllable permanent electromagnet and an iron plate were used for releasing or elevating the drooping eyelid, depending on the estimated degree of eyelid closing or opening movements. The system effectively assisted patients in opening their eyelids, reduced complications, and was convenient to use.

## V. CONCLUSION

In this study, a novel assistance system was designed to automatically assist in the symmetric and synchronous elevation of the paralytic upper eyelid of patients with unilateral blepharoptosis. In the proposed system, an optical probe was used for detecting the state of the eyelid being closing or opening, and the controllable permanent electromagnet and the iron sheet affixed to the upper eyelid were used for elevating the drooping eyelid according to the estimated state of the eyelid being closing or opening. Moreover,

the brackets were designed to be adjustable to achieve the appropriate distance between the optical probe and the eyes and accommodate various facial shapes. From the experimental results, the accuracy of the proposed system in detecting eyelid closure while a patient was sitting was approximately 92%, and the system also achieved a high performance level when patients were walking or engaging in facial movements. Moreover, the proposed system objectively demonstrated good efficacy in elevating drooping eyelids by achieving a mean gain of  $3.5 \pm 0.4$  mm. The IPFL for most patients was effectively improved and restored to a normal value by using the system. Unlike conventional surgeries and other assistive devices, the proposed system could provide the following advantages of a low treatment risk and a low cost. Moreover, the results of the questionnaire also indicated that the proposed system was subjectively judged by patients to provide superior comfort and efficacy. This proposed system could be considered as a useful prototype, as it could assist in the symmetric and synchronous elevation of a paralytic upper eyelid and might achieve complete improvement in patients with mild-to-moderate ptosis and partial improvement in patients with severe ptosis in terms of efficacy (improvement in IPFL) and aesthetics. This study has been continued for long-term assessments. In addition, whether the system provides a superior visual field as assessed by a Goldman visual field test or a Humphrey visual field test must be further studied. It is expected that the device may be used not only for improving symptoms but also preventing complications (e.g., amblyopia, strabismus, and astigmatism in children) from the disease in the future.

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